A STUDY OF A MODEL REFERENCE ADAPATIVE POWER SYSTEM STABILIZER

by

RAPARLA ARUNA KUMARI

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

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RAPARLA ARUNA KUMARI

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AUGUST, 1991

CERTIFICATE

Certified that this work *A STUDY OF A MODEL REFERENCE ADAPTIVE POWER SYSTEM STABILIZER* by *Ms. R Aruna Kumari* has been carried out under my supervision and that this has not been submitted elsewhere for a degree.

26/7/91

(S. S. PRABHU)
Professor
Department of Elecrical Engineering
Indian Institute of Technology
Kanpur.

ACKNOWLEDGEMENTS

I am not finding words to express my heartfelt gratitude to my thesis supervisor Dr S.S. Prabhu, for his guidance, encouragement and constant inspiration. He only introduced me to the area of power system dynamics and taught me various things

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ABSTRACT

This thesis presents a study of state feedback model reference adaptive control technique using Lyapunov's second method for the design of power system stabilizer (PSS). The reference model incorporates the desired characteristics of system performance.

A numerical power system problem has been considered and an adaptive PSS designed for it Detailed simulation study of the behaviour of the controlled system has been done at various operating conditions and system strengths to establish the efficacy of the procedure.

Since all the state variables are not available in practice, and since even the system parameters are not known, reconstruction of the state variables by the usual procedure is not possible. Here, since if the adaptive system works properly, the controlled system tends towards the reference model due to the adaptation process, it was felt that observers based on reference model parameters and plant outputs may work satisfactorily. Detailed numerical experimentation has established that a third order observer, which uses only the angular velocity signal from the generator, cascaded with the state feedback adaptive controller gives highly satisfactory results.

TABLE OF CONTENTS

LIST OF SYMBOLS

Δ	Subscript to denote small changes about the operating point
o	Subscript to denote the value of the operating point
t	Time in seconds
ω_o	Synchronous angular velocity in radians per second
ω	Instantaneous angular velocity of rotor in radians per second
δ	Rotor angle with respect to system reference in radians
E	Infinite bus voltage magnitude in p u.
V_t	Generator terminal voltage magnitude in p.u.
X_d , X_q	d and q axes synchronous reactances
X_d'	d axis transient reactance
τ_{do}'	d axis transient open circuit time constant
H	Inertia constant in seconds
M	$(2\,H/\omega_o)$
T_e , T_e'	Electrical torque developed
T_m	Mechanical torque input
R_e	Resistance of transmission line in p.u.
X_e	Reactance of transmission line in p.u.
K_e	Voltage regulator gain
τ_e	Voltage regulator time constant
E_{fd}	Correcting feedback signal from output of Exciter
t	superscript to denote transpose

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

To improve system transient stability, fast acting high gain AVRs with static excitation systems are used with modern alternators. But, they have deleterious effect on dynamic stability, resulting, often, in lightly damped and even sustained oscillations,typically in the range of 0.2 to 2 Hz. Thus it can be assumed that the modern voltage regulator introduces negative damping. To offset this effect and to improve system damping, artificial means of producing damping torques have been developed. These means essentially produce torque components in phase with generator rotor speed and involve use of an auxiliary circuit in the excitation control loop. The output of the auxiliary circuit is added to the main voltage feedback of AVR. These circuits have been traditionally called as power system stabilisers (PSS). Their input is a signal from rotor speed,accelerating power or generator bus frequency.

Various methods have been reported in the literature for the design of PSS. Earlier designs were based on classical control theory and the recent works are based on modern control theory. The following paragraphs give a brief review of the important works done in PSS design.

1.1 Non Adaptive PSS

In this design method, the PSS structure and parameters, once designed, will not change with time or operating conditions or system configuration. Such PSS will give good results only if the operating condition does not change much from that used for PSS design. An extensive list of methods falling into this category is available in the literature; see for example [22, 23], only a few of them are discussed, here.

Extensive study in this field started with the paper of deMello and Concardia[1] which explained the problem of dynamic stability in terms of the concepts of synchronous

and damping torques and proposed design of PSS using classical frequency domain techniques. Bollinger et. al. [2] used the root locus technique to shift the eigen values, corresponding to rotor oscillations, to suitable locations Hamdan and Hughes [3,4] used multivariable frequency response plots for design and analysis of PSS. Based on linear regulator theory, Yu et. al. [5] have designed the stabiliser as an optimal state feedback controller, which minimises a quadratic performance index (PI). The resulting controller, in this method, improves the closed loop performance, but the inaccessibility of some of the states for feedback creates a problem in practical applications. Suboptimal controllers with the system represented by lower order models, with only measurable states as state variables, have been developed by Yu and Siggers [6].

Pole assignment techniques have been considered by many authors for the problem of power system stabilization. This approach provides a design method for PSS with the control objective of assigning the dominant closed loop eigen values to specified stable locations using either state feedback or output feedback. From a practical view point, pole assignment using output feedback is more important. Padiar et. al. [7] have presented three methods for the design of PSS by pole assignment with output feedback. Srinivas and Ramar [8] have designed first and second order PSS using pole placement with output feedback. Chow and Sanchez–Gasca [9] have presented four methods for PSS design, namely, full state feedback, output feedback by projective control method, full order observer and dynamic compensator by the projective control method with main emphasis on frequency response charecteristics of PSS transfer functions.

In practice, a power system will be very large consisting of hundreds of generating units. The analysis of such a large system will be very difficult, if it is represented in terms of the exact equivalent circuits of each and every machine. Undrill et. al. [24] have proposed a method for the analysis of large power systems by separating the whole power system into two parts, namely, the study system and the external system. The study system consists of a few machines of extreme importance and it is represented exactly. The

external system consists of the remaining machines, which are very large in number but of secondary concern These machines are represented by their dynamic equivalents

Rogers and Kundur, in the discussion of [25], recommended the dynamic reduction technique of Gremond and Padmore [26] for the analysis of large power systems. In this technique, each coherent group of machines is represented by an equivalent single machine. This technique is very effective in reducing system size.

Wong et. al [28] have developed an algorithm for the analysis of dynamic stability of very large power systems consisting of more than thousand machines. This method is very effective in determining the interarea stability. Here the exciter modes are masked and a search is made for electromechanical modes. This algorithm is based on the essentially spontaneous oscillations in power systems, developed by Byerly et. al. [27]. Unlike the early studies, where D Q (direct axis and quadrature axis) variables are used, here, P N (positive sequence and negative sequence) variables are used.

Uchida and Nagao [29] have proposed an S matrix method for the determination of eigen values of large electric power systems. In this method, the A matrix of the plant is transformed into the S matrix and the dominant eigen values are identified. This method is very fast due to the sparsity and structural uniformity of S matrix.

1.2 Adaptive PSS

A stabiliser designed using conventional control theory at one operating point may not give satisfactory performance at other operating points. In such situations, adaptive PSS are to be employed, which automatically sense and correct themselves whenever significant changes in system parameters occur. All the major adaptive control techniques, namely, model reference adaptive control (MRAC), self tuning regulators (STR), gain scheduling schemes and variable structure control have been considered for adaptive PSS design. A brief review of the major works in these areas is given below.

1.2.1 Self Tuning Regulator (STR) Techniques

Design of adaptive PSS as a STR has become feasible because of developments in microprocessor technology. These are digital adaptive control schemes and involve parameter estimation and control. In explicit STR, parameter values are explicitly obtained and used for generating control signals. In implicit schemes, parameter estimation is implied but is not done explicitly. Recursive least squares procedures are the most popular for identification

Ghosh et. al. [10] summarise the features of MRAC and four versions of self tuning controllers (STC) for adaptive PSS. In [11], the same authors have designed an adaptive PSS for large disturbances using recursive least squares (RLS) technique for parameter identification. By testing the PSS on an experimental micromachine system, it has been shown that this self tuning PSS gives better results than those with a fixed parameter stabilizer. Kanniah et al [12, 13] have used an implicit type STC, with RLS technique for parameter identification. Simulation results in [12] show that the dual rate STC, where two different sampling rates, one for identification and the other for control, are used, performs better than the single rate STC. In [13], the hardware and software used to implement dual rate STC for controlling a laboratory alternator system, are described. Xia and Heydt [14] have developed an STC approach for PSS design for a generator connected to an infinite bus through a long transmission line. The salient points of the controller are its adaptive nature and application of a least squares formulation for parameter estimation. The power system is stable over a wide range of operating conditions. Chandra et. al. [15] have implemented a self tuning excitation controller performing the functons of AVR and PSS along with an interactive man–machine interface using two microcomputers.

1.2.2 Gain Scheduling Schemes

In this scheme, a range of operating conditions, which are encountered in practice, are taken into consideration. Extensive offline design and simulation effort are needed to

obtain a suitable gain scheduling scheme. So, this scheme is very time consuming.

A simple adaptive PSS using gain scheduling approach has been developed by Brown Boveri company [16]. For discrete values of operating points and system strengths, suboptimal gains are calculated apriori and stored in the memory of a microcomputer in the form of a three dimensional lookup table. Depending upon the operating point, they are retrieved for PSS tuning. Sen Gupta [22] used the properties of tensor invariance to isolate sources of positive damping and synchronizing torques. Synchronizing and damping torques are exactly quantified. The PSS developed cancels the negative damping generated by AVR, and aug ments the positive damping part of its contribution. Ashok Pal [17] has designed PSS for large disturbances. An extended Kalman filter attached to a detection scheme is used for identification. Using the results of identification and after detailed digital simulation, two lookup tables, containing optimum PSS gains for different operating points, are formed. Using these lookup tables and using linear interpolation, PSS parameters are obtained for any given operating point.

Bandyopadhyay and Prabhu [30] have proposed a new approach for the design of adaptive PSS using gain scheduling technique. Five different constant gain PSS are designed for five operating conditions. All these five PSS operate in parallel. At any operating point, the control signal for stabilization is obtained as a weighted sum of the outputs of the individual PSS. The weighting factors are determined using a simple algorithm. This adaptive composite PSS (ACPSS) performs satisfactorily over a wide range of operating conditions.

Recently, Madhu and Prabhu [31] have proposed a method for the design of robust adaptive composite PSS (RACPSS) making implicit use of gain scheduling schemes. In this method, a set of PSS is designed. Depending upon the operating condition an appropriate PSS is selected from the set using a simple algorithm. It is shown here that a maximum three individual PSS are sufficient for satisfactory performance of the system. The algorithm used here is simpler and easier than that used for the design of ACPSS.

1.2.3 Variable Structure Schemes (VSS)

VSS essentially involve nonlinear state feedback control. The control law involves switching, whenever the system state crosses a 'switching hyperplane' in the state space. Since the structure of the feedback changes depending on the position of state point, these schemes are called variable structure schemes. Once a state point reaches a switching hyperplane, it is made to travel on the hyperplane, during control Thus, as soon as a disturbance changes a state point from its equilibrium value in a system with regulating control, the controller brings it back to the equilibrium point by making it move on the switching hyperplane. Motion of the system on the switching hyperplane is called 'sliding mode of operation' An advantage of these controllers is that control action takes place even in the presence of parameter variations. In many cases, the physical realisation of such a controller can turn out to be very simple. Switching action permits the use of limiting values of control input magnitudes thus leading to high speed of response. The only drawback of these schemes is the excessive 'chattering' of the controller which is undesirable, in practice, from the point of view of both controller and plant hardware. Hsu and Chan [18] have attempted PSS design as a variable structure stabilizer. Serious work in VSS for power system stabilization has not been done. Strictly speaking, VSS should be looked at as adaptive controller, since it does not attempt to change the controller on the basis of variation in plant parameters. However, it is possible to develop VSS in the MRAC setting as is done by Ambrosino et. al. [32].

1.2.4 Model Reference Adaptive Control (MRAC) Technique

Irving et. al. [19] described MRAC for generator voltage regulation based on maintaining an unconditionally stable adaptive loop using Popov's hyperstability theory.

Ibrahim and Kamel [20] have proposed a model reference adaptive PSS (MRAPSS). They claim that this PSS improves the dynamic stability of power system by effectively increasing the damping torque of the synchronous generator in the system. They have used

Lyapunov technique to assure stability of the system with PSS. In this work, they have chosen a second order transfer function for the power system, with torque as output and speed as input, with no zeros. But, the transfer function is in fact a third order one with three poles and two zeros. They have tried to design a first order PSS. But, a first order PSS is not at all acceptable for practical purposes. They have compared a component of electrical torque, which is proportional to the q–axis component of voltage behind transient reactance, of the plant with that of the model. But, this component of torque is not at all physically available separately from the total electrical torque. Simulation results are wrong, since even the calculation of well–known coefficients k_1, k_2, k_3, k_4, k_5 and k_6 is wrong. So, this scheme, under no circumstances, can be considered for the design of PSS. Ghandakly and Idowu [21] have presented a decentralized MRAC scheme for the design of PSS and a means for coordinating the generator unit excitation and governor control loops. System stability is assured by deriving the adaptive control law from Lyapunov energy function.

1.3 Scope of the Present Work

The present work is concerned with computer aided design of MRAPSS, which performs satisfactorily over a wide range of operating conditions. System stability is assured by deriving the adaptive controller from application of Lyapunov's second method. In this scheme, the state variables of the power system under consideration (the plant) are to follow those of an explicitly specified reference model, which is designed to have desirable performance charecteristics. In general not all the state variables are available for feedback. So, the unavailable states are reconstructed using reduced order observers and the effectiveness of MRAPSS is investigated.

1.4 Outline of the Rest of the Thesis

Chapter 2 describes the power system considered. A brief discussion on modelling of

the power system for dynamic stability studies is also given It is followed by a brief survey of the PSS input signals used in the traditional PSS, in the literature. Then, the PSS input signals used in the present work, are given.

In chapter 3, a brief introduction to model reference adaptive systems (MRAS) and their design methodologies are given. The PSS design problem is posed as a MRAS design problem. Lyapunov's synthesis technique is used for designing the adaptive controller, which ensures system stability. A numerical problem is considered. First, assuming all the states to be available, a model reference adaptive controller with parallel structure and having full state feedback is determined and the resulting system is simulated over a wide range of operating conditions. Since all the states are not available, in practice, reduced order observers are next designed for reconstructing the unavailable states. Design of the observers needs knowledge of the plant parameter matrices. These matrices, however, are not known. We can use an adaptive observer along with a state feedback adaptive controller. However, what happens when the two systems, namely, the adaptive observer and the adaptive controller, designed seperately, are used together, is not known. Furthermore, the resulting system complexity may discourage its use in practice. So, instead of the above approach, we have used the parameter matrices of the reference model for state observation. Since, in steady state, the plant with the feedback controller is expected to converge to the reference model, it is hoped that, asymptotically the state observation leads to the actual state values of the plant and the adaptive system would be stable, just as the full state feedback MRAOS designed using Lyapunov's direct method.

Assuming that one, two and three state variables are unavailable at a time, first, second and third order observers are respectively constructed, and the system responses are examined for all the three cases over a wide range of operating conditions. Good results have been obtained suggesting that the approach taken up is efficacious.

Chapter 4 contains conclusions and suggestions for further work.

CHAPTER 2
MODEL OF POWER SYSTEM

High gain, fast acting modern voltage regulators often lead to sustained low frequency oscillations in power systems. In order to damp out these oscillations and assure dynamic stability, an auxiliary controller is used in the exciter control loop

In this chapter, the model of the power system considered for the study of dynamic stability is presented.

In its simplest form, a power system consists of a synchronous generator connected to an infinite bus through a transmission line. In the literature, various state space models of this system having varying degrees of complexity and accuracy are available. In the classical model, the synchronous machine is represented by a voltage source behind the machine direct axis transient reactance. Though this model is very simple, it does not account for the demagnetising effect of armature reaction.

The popular Heffron–Philips model has been widely used by many researchers for the study of dynamic stability. This model is almost as simple as the classical model and offers a good physical understanding of the synchronous generator while taking the demagnetising effect of armature reaction into consideration. It neglects the fast dynamics associated with the damper windings since these are not of importance in the usual dynamic stability studies. Heffron–Philips model and the slightly more complex '$1\frac{1}{2}$ model' [33] have, perhaps, become the standard models for dynamic stability studies. There are, however, problems for example those associated with subsynchronous resonance (SSR), where more detailed models would be needed. The models used for dynamic stability studies are all linear models defined around the system operating point.

In the present work, we have confined our attention to the Heffron–Philips model.

2.1 Heffron–Philips Model (State Space Representation)

In the development of the model, the following assumptions are made:

1. The effects of damper windings are neglected.
2. Stator winding resistance is neglected.
3. The speed voltage terms are dominant over the rate of change of flux linkages terms.
4 Balanced conditions are assumed and saturation effects are neglected.
5. The electrical network is considered to be in quasi–steady state.

The power system considered is shown in Fig 2.1. It consists of a single machine with an AVR connected to an infinite bus through a transmission line. The Heffron–Philips model of the system around an operating point is represented in block diagram form in Fig 2.2, [34].

The Heffron–Philips model of the power system can be expressed in state space format as

$$\dot{x} = A\,x + B\,u \tag{2.1}$$

$$y = C\,x \tag{2.2}$$

where

$$x = [\,\delta_\Delta \;\; \omega_\Delta \;\; e'_{q\Delta} \;\; e_{fd\Delta}\,]^t \tag{2.3}$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ a_1 & 0 & a_2 & 0 \\ 0 & 0 & a_3 & a_4 \\ a_5 & 0 & a_6 & a_7 \end{bmatrix} \tag{2.4}$$

$$B = [\;0 \;\; 0 \;\; 0 \;\; b]^t \tag{2.5}$$

The output variable y is defined to be that which appears as PSS input. Many different PSS input signals are used in practice. The matrix C thus depends on the input

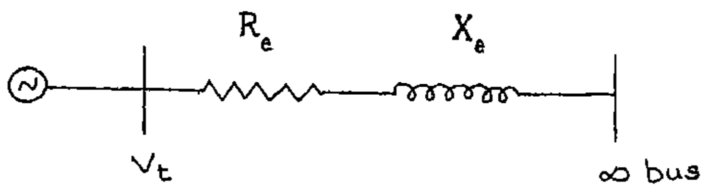


Fig 2.1 One Line Diagram Of Power System

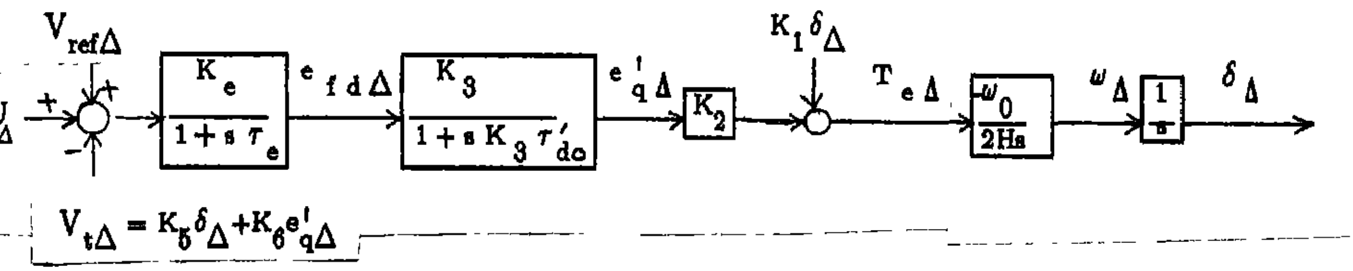


Fig 2.2 Block Diagram Of Power System

signal used by the PSS in a given situation.

A brief derivation of the model is given in Appendix 1 along with definitions of coefficients a_1 , a_2 , a_3 , a_4 , a_5 , a_6 , a_7 and b.

2.2 Input Signals to PSS

In PSS design, proper selection of input signals is important. Feedback of rotor speed deviation appears to be proper, since the objective of PSS is to provide adequate damping of electromechanical oscillations. Speed input signal has been used by many researchers. Other signals, such as terminal voltage, armature current, active and reactive powers, accelerating power and frequency can also be used as input signals to PSS

Larsen and Swann [23] have analysed the effectiveness of speed, power and frequency signals for PSS. They have used frequency domain arguments based on classical control theory.

Anwar [35] has examined the suitability of PSS input signal in terms of stability robustness of the system, i.e., in terms of regions in the P–Q plane, where the system remains stable. In this study, he has used a state space description of power system. Here P is the active power and Q is the reactive power of the generator From the practical experience at Ontario Hydro, Canada, Kundur [36] has given a brief discussion on the effectiveness of various input signals. Madhu [37], utilising the idea of robustness,clearly showed the superiority of two input PSS, with speed and acceleration as inputs, over single input PSS.

In the present work, we use the full state vector as PSS input signal. In practice, all the state variables considered are not directly available for measurement and will have to be obtained through some kind of observation scheme. These matters will be taken up in the sequel.

CHAPTER 3
MRAC TECHNIQUE FOR PSS DESIGN

In the first chapter, the importance of PSS in damping out low frequency electromechanical oscillations in power systems has been described. It has also been indicated that a fixed parameter stabilizer designed at a particular operating point may not give satisfactory performance when the operating point changes. In practice, the operating point, which depends upon load conditions, changes continually. Therefore, PSS should adapt itself to the changing load conditions. Unlike fixed gain or fixed parameter stabilizers, the adaptive stabilizer determines a new set of control parameters as changes occur in system configuration and load levels, thereby ensuring that the controller parameters are efficacious for a wide range of operating conditions. The model reference approach for PSS design has the definite advantage of stability assurance which is lacking in self tuned regulator design. Furthermore, higher adaptation speeds can be obtained with MRAC, [38].

A design technique, which involves the application of MRAC concept for the purpose of designing a PSS placed in the excitation control loop is described in this chapter. In this scheme, a reference model into which the design specifications are incorporated is introduced and the states of the plant are forced to follow the states of the specified reference model. Adaptation signals are derived for the exciter input to assure overall system stability as well as the desired system performance. This design scheme is verified on an example synchronous generator connected to an infinite bus through a transmission line. Since all the states of the generator are not always available, numerical experimentation is done to know what happens if the unavailable states are reconstructed using state observers. By simulating the overall system over a wide range of operating conditions and for different system strengths, it is shown that a third order observer which reconstructs states δ_Δ, $e^1_{q\Delta}$ and $e_{fd\Delta}$ using the state ω_Δ, gives satisfactory design of PSS.

3.1 Introduction to MRAS [38]

MRAC systems are important since they lead to systems with a fairly high speed of adaptation, as there is no need for estimation of plant parameters. In MRAC, the aim is to make the states of the unknown plant approach asymptotically the output of a given reference model, which is part of the control system. The difference between the states of the reference model and those of the adjustable system is used by the adaptation mechanism either to modify the parameters of the adjustable system (called *parameter adaptation*) or to generate an auxiliary input signal (called *signal synthesis adaptation*) in order to minimise the difference between the states of the adjustable system and those of the model. The basic scheme of MRAC is given in Fig 3.1

In terms of controller structure, MRAS are classified into three types:

1. Series MRAS:

Here the adjustable system and the reference model are in series, Fig 3.2.

2. Series Parallel MRAS:

There are two cases here.

i. The reference model is in two parts, one in series with the adjustable system and the other in parallel, Fig 3.3 1

ii. The adjustable system is in two parts, one in series with the reference model and the other in parallel, Fig 3.3.2.

3. Parallel MRAS:

This is the most commonly used scheme. Here, the reference model is in parallel with the adjustable system, Fig 3.4.

We have confined our attention to the parallel MRAC structure in the present work.

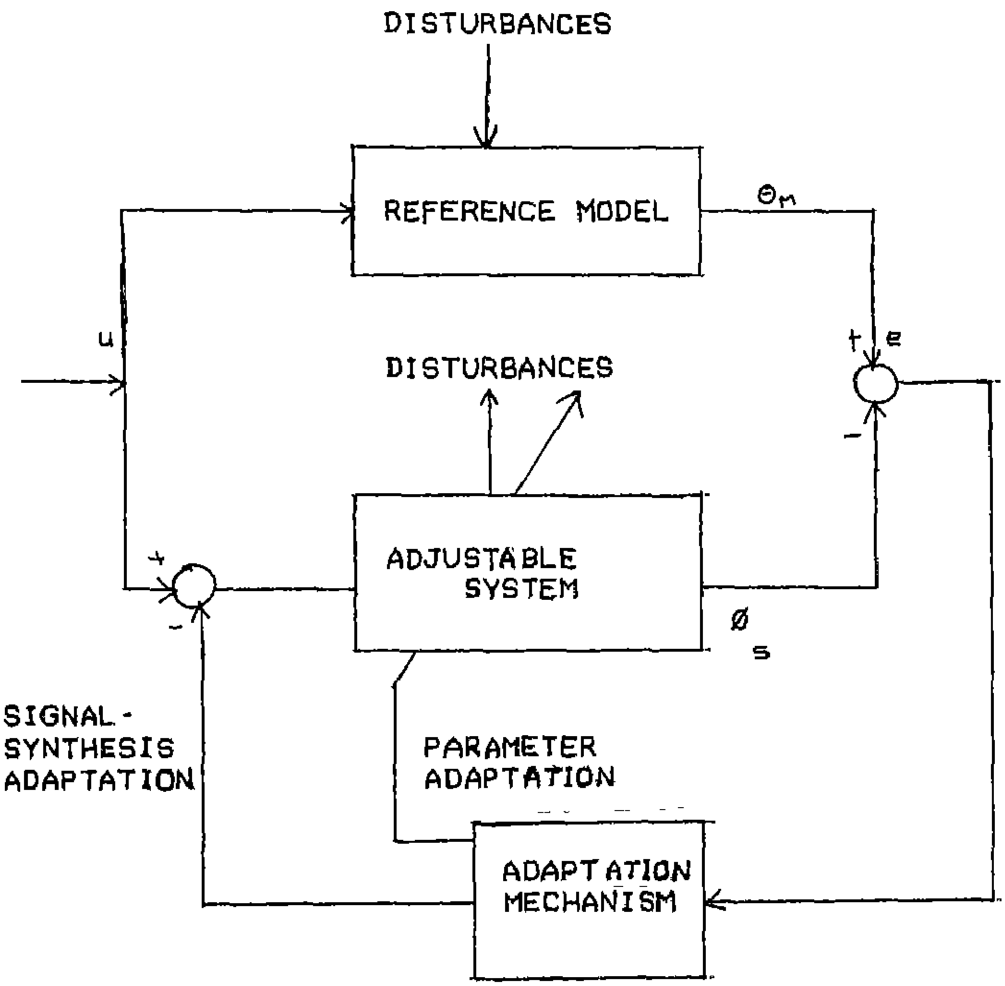


Fig 3.1 Basic Configuration of A MRAS

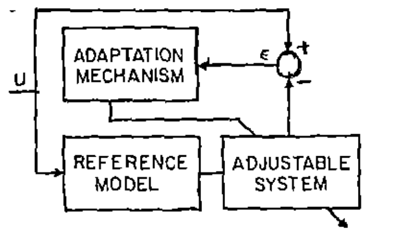


Fig 3.2 Series MRAS

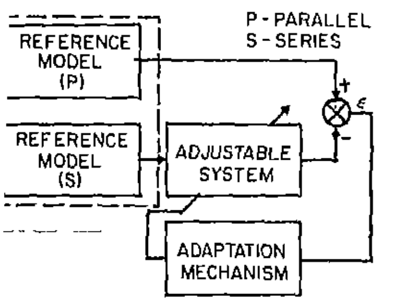


Fig 3.3.1 Series Parallel MRAS

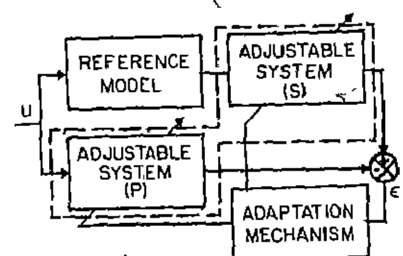


Fig 3.3 2 Series Parallel MRAS

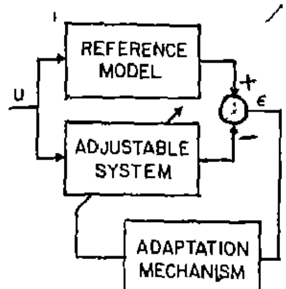


Fig 3.4 Parallel MRAS

3.2 Design Methodologies [38]

Most of the techniques proposed for design of MRAC reduce the adaptation problem to that of determining the controller structure and finding how the controller parameters are to be adjusted, that is ,obtaining a parameter adaptation law to guarantee global asymptotic stability. There are three important techniques for the design of continuous time model reference adaptive controller, namely, the MIT rule and related methods, the Lyapunov approach and Popov's hyperstability approach.

3.2.1 MIT Rule

The MIT rule does not assure system stability. A good compromise is made between stability and speed of adaptation.

Here, the input r(t) of the system is applied to appropriately designed reference model to generate the desired output. The integral of the square of the error between this desired output and the output of the plant is minimised.

The performance index (PI) is given by

$$J = \int_0^T \| y_m(t) - y(t) \|^2 \, dt \tag{3.1}$$

where

y_m is the output of the reference model and

y is the output of the plant (adjustable system)

It is assumed that the speed of adaptation is low and the system parameter values are always in a sufficiently small neighbourhood of model parameter values.

Since the minimisation is to be performed online, the performance can be evaluated over a sufficiently small time interval Δt. Over Δt, PI is

$$J_p(b) = \frac{1}{2} \| y_m(t) - y(t) \|^2 \tag{3.2}$$

Here b is the adjustable parameter.

$J_p(b)$ is dependent on t and is to be minimised with respect to b by using a search technique, after it has attained a steady state value. The search techniques are

implemented using sensitivity functions, which must be generated online

One of the search techniques to generate the adaptation algorithm is the gradient method. The standard gradient search algorithm may be used to generate estimates of the parameters.

$$\dot{b}(t) = -B\frac{\partial J}{\partial b} = B\frac{\partial y}{\partial b}e(t) \tag{3.3}$$

where

B is an arbitrary positive constant called the adaptive gain,

$$e = [y_m(t) - y(t)] \tag{3.4}$$

and $\frac{\partial y}{\partial b}$ is the sensitivity matrix.

The equation (3.3) gives the MIT rule.

The MIT rule was popular because of its simplicity in practical implementation. But this must be used with caution, inview of possible instability. Furthermore, some other drawbacks are:

1. The initial difference between the parameters of the reference model and those of the adjustable system is assumed to be small.

2. The adaptation speed is also assumed to be less.

3. There is no indication given regarding the selection of the adaptation gains in order to assume the convergence of the adaptation process and the stability of the MRAC system.

3.2.2 Lyapunov Approach [38]

In order to achieve good design, it is to be made sure that the system along with the controller is stable. Stability can be ensured by using Lyapunov approach or hyperstability approach in designing controllers.

In Lyapunov approach, the first step is to determine the differential equation which describes the error between the states of the model and that of the plant. Then the parameter adjustment equations are obtained as the conditions to assure the error differential equation, stable. In order to do this, a positive definite Lyapunov function is

chosen. Then, the adaptive mechanism equations are derived so as to cause the time derivative of the Lyapunov function negative semidefinite This negative semidefiniteness of the Lyapunov function ensures system stability and the error is also made to go to zero, as $t \to \infty$.

The main difficulty with the Lyapunov approach is that the entire state vector must be available for measurement and this is not always possible. Another drawback is that the Lyapunov design rule may not be applicable to cases where the plant parameters can not be directly adjusted. In cases, where a Lyapunov function can not be found, the hyperstability approach can be used.

3.2.3 Hyperstability Approach

Popov [39] introduced the concept of hyperstability as a natural extension of absolute stability. Landau [40] proposed application of this concept for the design of adaptive control systems.

For application of hyperstability conditions, the MRAC system (MRACS) is expressed as a *standard* system (Fig 3.5), with a linear time invariant operator in the forward path and a passive non linear operator in the feedback path. The non linear operator satisfies Popov Integral Inequality, [38] The system is then asymptotically hyperstable if the transfer function matrix of the linear block is strictly positive real, [38]. To apply this approach to MRACS, it is necessary to express the error equation in the *standard form*. Hyperstability conditions enable determination of feedback block,N (Fig.3.5) which constitutes the adaptation law.

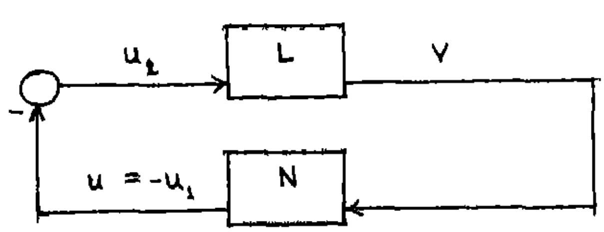


Fig 3.5 Standard Feedback System

Landau's Procedure for the Determination of MRACS, [38]:

Step 1 : The MRACS is transformed into an equivalent standard feedback system composed of two blocks as shown in Fig 3 5, which is always possible.

Step 2.: The solutions for the part of the adaptation laws which appear in the feedback of the equivalent system are found such that the Popov integral inequality,

$$\int_0^T u^t \, v \, d\tau \geq -\gamma_0^2 \tag{3.5}$$

is satisfied. Here, u and v are as shown in Fig 3.5

Step 3 : The solutions for the remaining part of the adaptation law, which appears in the feedforward path, are found such that the transfer function matrix of the feedforward path is strictly positive real. This ensures global asymptotic stability of the entire system.

Step 4 : Return to the original MRACS in order to specify the adaptation law explicitly, that is, the structure of the mechanism.

Since this approach requires the use of derivatives of error, when only some of the states of the model and adjustable system are available, this gives a significant difficulty. The Lyapunov approach and the hyperstability are equally efficient, but in many cases, hyperstability approach may be easier to apply than Lyapunov approach.

In the present work, we have used state feedback MRAC method with Lyapunov synthesis technique for the design of PSS.

3.3 Comparison of MRAC with STR

MRACS are easy to implement with a fairly high speed of adaptation. They can be used in variety of situations. MRAC can be used with continuous as well as discrete systems, whereas STR can be used only with discrete systems. MRACS are mostly applied in deterministic systems, whereas STR are essentially stochastic systems. Recent research showed the equivalence of MRAC and STR methods. Well designed STR have the advantage of being able to adapt to any disturbances. MRACS have the definite advantage

that the design ensures overall system stability. This assurance is lacking in STR

3.4 State Feedback MRAC Using Lyapunov Synthesis Technique

The basic configuration of state feedback MRACS is shown in Fig 3 6

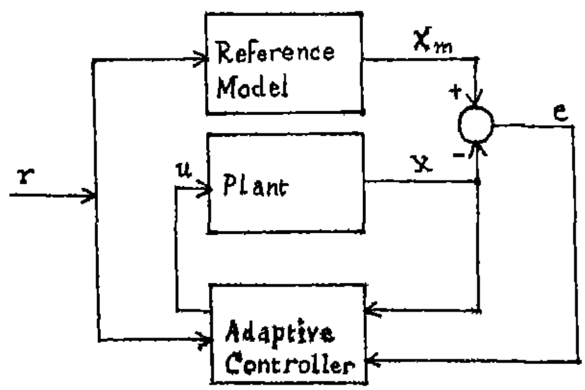


Fig. 3.6 Basic Configuration of State Feedback MRACS

The state equation of stable reference model is

$$\dot{x}_m = A_m x_m + B_m r \tag{3.6}$$

and that of the linear time invariant plant is

$$\dot{x} = Ax + Bu \tag{3.7}$$

Here, x_m and x are n–dimensional state vectors and r and u are m–dimensional control vectors.

The state error vector is defined as

$$e = x_m - x \tag{3.8}$$

The differential equation for the error is given by

$$\dot{e} = A_m e + f \tag{3.9}$$

where

$$f = (A_m - A)x + B_m r - Bu \tag{3 10}$$

In order to drive the state error vector to zero by feedback synthesis using Lyapunov's direct method, a positive definite function of the form

$$V = e^t Pe + h(\varphi, \psi) \tag{3.11}$$

is selected as a candidate Lyapunov function where P is a symmetric positive definite matrix and $h(\varphi, \psi)$ is a functional expression for the misallignment between the reference model parameters and the plant parameters. Misallignment parameter vectors φ, and ψ are defined in terms of the elements of the matrices $(A_m - A)$ and $(B_m - B)$ respectively.

The control objective for a stable system is to specify a control law such that the first derivative of the candidate Lyapunov function, $\dot{V}$ is negative semi definite. This implies the stability of error system. If an adaptation law is so chosen that $\dot{V} \equiv 0$ implies $e(t) = 0$, then by a theorem of La Salle, $e(t) \to 0$ as $t \to \infty$. This means the controlled system is asymptotically stable

Now let us have a state feedback of Kx and a feedforward of Σu for the plant. In that case, the plant state equation, with the above control incorporated, becomes

$$\dot{x} = (A + B\Sigma K)x + B\Sigma u \tag{3.12}$$

For exact model matching, we need existence of matrices K^* and Σ^* such that

$$B\Sigma^* = B_m$$
$$A + B_m K^* = A_m \tag{3.13}$$

It is assumed that both B_m and B are of full rank so that Σ^* is non-singular. The equation, satisfied by the state error vector, e is

$$\dot{e} = A_m e + (A_m - A - B\Sigma K)x + (B_m - B\Sigma)u \tag{3.14}$$

It can be shown that the above equation can be expressed as

$$\dot{e} = A_m e + B_m \varphi x + B_m \psi \Sigma(u + Kx) \tag{3.14}$$

where

$$\varphi = [K^* - K(t)] \text{ and}$$
$$\psi = [\Sigma^{-1}(t) - \Sigma^{*-1}] \tag{3.15}$$

For the error equation, we choose

$$V = \tfrac{1}{2}\,[e^t Pe + \mathrm{tr}\,\{\varphi^t\, \Gamma_1^{-1}\, \varphi + \psi^t\, \Gamma_2^{-1}\, \psi\}] \tag{3.16}$$

where

$$\Gamma_1 = \Gamma_1^t > 0 \text{ and}$$
$$\Gamma_2 = \Gamma_2^t > 0 \tag{3.17}$$

It can be derived, [41], that, if we have

$$\dot{\varphi} = -\Gamma_1 B_m^t P e x^t \text{ and}$$
$$\dot{\psi} = -\Gamma_2 B_m^t P e \,(u + Kx)^t \Sigma^t \tag{3.18}$$

The stability of equation (3.14) in the (e, φ, ψ) space is guaranteed In the above equation, P is a positive definite matrix satisfying

$$A_m^t P + P A_m = -Q, \qquad Q = Q^t > 0 \tag{3.19}$$

The adaptive control law in terms of k(t) and $\Sigma(t)$ is

$$\dot{K}(t) = \Gamma_1 B_m^t P e x^t$$
$$\dot{\Sigma}(t) = \Sigma \Gamma_2 B_m^t P e \,(u + Kx)^t \Sigma^t \Sigma \tag{3.20}$$

It should be noted that (see [41]) stability is not assured in general over the whole (e, K, Σ) space. A necessary condition for stability is that the initial values $e(t_0)$, $K(t_0)$ and $\Sigma(t_0)$ should satisfy

$$V(t_0) = \tfrac{1}{2}\,[e^t(t_0)\, P e(t_0) + \operatorname{tr}\{\, (K^* - K(t_0))^t\, \Gamma_1^{-1}(k^* - K(t_0) + (\Sigma^{*^{-1}} - \Sigma^{-1}(t_0))^t\, \Gamma_2^{-1}$$
$$(\Sigma^{*^{-1}} - \Sigma^{-1}(t_0))\}] \;<\; \tfrac{1}{2}\operatorname{tr}[\,(\Sigma^{*^{-1}})^t\, \Gamma_2^{-1} \Sigma^{*^{-1}}\,] \tag{3.21}$$

Thus, it is necessary to start with sufficiently small values for $e(t_0)$, $K^* - K(t_0)$ and $\Sigma^* - \Sigma(t_0)$.

3.5 Posing of PSS Design Problem as a MRAC Design Problem

The state space model of the power system for the purpose of PSS design has the form

$$\dot{x} = Ax + Bu \tag{3.7}$$

where A is 4x4 matrix, B is 4x1 matrix, x is 4x1 vector and u is the scalar input.

The reference model is represented as

$$\dot{x}_m = A_m x_m + B_m r \tag{3.6}$$

The state variables in the above equation are

$$x = [x_1\ x_2\ x_3\ x_4]^t = [\delta_\Delta\ \omega_\Delta\ e'_{q\Delta}\ e_{fd\Delta}]^t \tag{3.22}$$

and $$x_m = [x_{m_1}\ x_{m_2}\ x_{m_3}\ x_{m_4}]^t = [\delta_{m\Delta}\ \omega_{m\Delta}\ e'_{qm\Delta}\ e_{fdm\Delta}]^t \tag{3.23}$$

The control matrices B and B_m are

$$B = B_m = [0\ 0\ 0\ b]^t \tag{3.24}$$

The matrix A is given in equation (2 4).

From the derivation of the power system model given in Appendix 1, it is clear that as the operating conditions defined by the complex power supplied by the generator changes, only the matrix A changes, the matrix B is unaffected. Thus, it is not necessary to have the feed forward term Σu in the design as given earlier and the adaptive control becomes

$$u = K(t)x + r \tag{3.25}$$

where u represents the control input to the plant. The closed loop system becomes

$$\dot{x} = (A + BK)x + Br \tag{3.26}$$

The matrix k is given by

$$\dot{K}(t) = \Gamma\,(B_m^t Pe)\,x^t \tag{3.27}$$

where

Γ is a symmetric positive definite matrix and

P is symmetric positive definite and satisfies the Lyapunov equation (3.19).

A_m is to be chosen such that it ensures the asymptotic stability of the reference model.

<u>Selection of reference model</u>·

The matrix A_m of the reference model is selected such that the poles of the system are placed in the permissible sector shown in Fig. 3.7. The power system chosen by us is essentially the same as that of Madhu [37] and we have chosen the same sector as was

chosen by him for PSS design by eigen value placement.

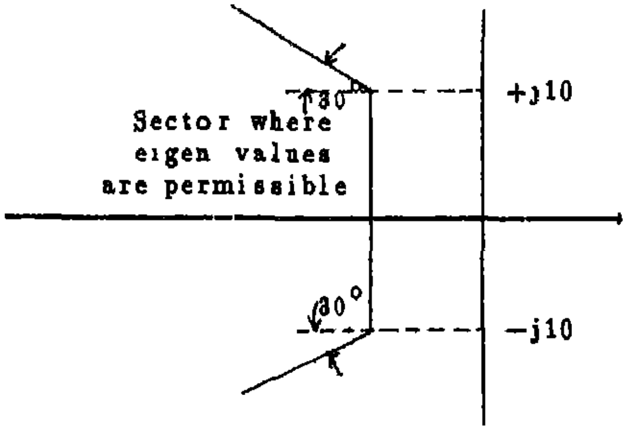


Fig. 3 7 Permissible Sector of Eigen Values

3.6 Numerical Problem (Full State Feedback)

For the data given in Appendix 2, at rated load and UPF

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -85.652 & 0 & -128\ 72 & 0 \\ 0 & 0 & -0.3914 & 0.2 \\ 575.3 & 0 & -3142.2 & -100 \end{bmatrix}, \ B = \begin{bmatrix} 0 & 0 & 0 & 5000 \end{bmatrix}^t \tag{3.28}$$

The open loop poles of the system are 0.56 ± j9 63, −8.29 and −93.2113.

We specify that A_m should have eigen values at −1 ± j8, −3.0 and −93.2113.

We will determine A_m by determining the 1x3 matrix G such that A + BG has the required eigen values. Then A + BG gives us A_m. It is found that

$$A_m = A + BG = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -85.652 & 0 & -128.72 & 0 \\ 0 & 0 & -0.3914 & 0.2 \\ -795.8 & -62.1 & -2065.6 & -97.82 \end{bmatrix} \tag{3.29}$$

where $G = [-0.274 \quad -1.242e{-2} \quad 0.215 \quad 4.36e{-4}]$ (3.30)

As mentioned earlier, B_m is chosen to be the same as B.

Let A_m be represented as

$$A_m = \begin{bmatrix} 0 & 1 & 0 & 0 \\ a_{m_1} & 0 & a_{m_2} & 0 \\ 0 & 0 & a_{m_3} & a_{m_4} \\ a_{m_5} & a_{m_6} & a_{m_7} & a_{m_8} \end{bmatrix} \tag{3.31}$$

Let Γ be chosen to be diagonal

$$\Gamma = \begin{bmatrix} \gamma_1 & 0 & 0 & 0 \\ 0 & \gamma_2 & 0 & 0 \\ 0 & 0 & \gamma_3 & 0 \\ 0 & 0 & 0 & \gamma_4 \end{bmatrix} \tag{3.32}$$

Q is chosen to be diagonal, and equal to qI, where $q > 0$ is a real scalar. For the chosen Q, the Lyapunov equation (3.19) is solved for P. Let the last row of P be $[p_1 \ p_2 \ p_3 \ p_4]$. Then, we study the resulting design, after incorporating the adaptive feedback law given by equations (3 25) and (3.27) by extensive simulation, for various operating conditions, using the software package SIMNON. The equations for simulation are the plant equations, the reference model equations and the nonlinear feedback controller equations. These equations are given below.

Plant:

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = a_1 x_1 + a_2 x_3$$

$$\dot{x}_3 = a_3 x_3 + a_4 x_4$$

$$\dot{x}_4 = a_5 x_1 + a_6 x_3 + a_7 x_4 + bu \tag{3.33}$$

Reference Model:

$$\dot{x}_{m_1} = x_{m_2}$$

$$\dot{x}_{m_2} = a_{m_1} x_{m_1} + a_{m_2} x_{m_3}$$

$$\dot{x}_{m_3} = a_{m_3} x_{m_3} + a_{m_4} x_{m_4}$$

$$\dot{x}_{m_4} = a_{m_5} x_{m_1} + a_{m_6} x_{m_2} + a_{m_7} x_{m_3} + a_{m_8} x_{m_4} + br \tag{3.34}$$

<u>Feedback Gains</u>:

$$\dot{k}_1 = T_m \gamma_1 x_1$$

$$k_2 = T_m \gamma_2 x_2$$

$$\dot{k}_3 = T_m \gamma_3 x_3$$

$$\dot{k}_4 = T_m \gamma_4 x_4 \tag{3.35}$$

Here, $$T_m = -b\ [\ p_1(x_1 - x_{m_1}) + p_2(x_2 - x_{m_2}) + p_3(x_3 - x_{m_3}) + p_4(x_4 - x_{m_4})\ ] \tag{3.36}$$

<u>Control Input</u>:

$$u = k_1 x_1 + k_2 x_2 + k_3 x_3 + k_4 x_4 + r \tag{3.37}$$

By experimentation, it was found that $\Gamma = I$ and $q = 10^{-3}$ resulted in adaptive controller design which not only gave stable response over a large range of operating conditions, but also exhibited good damping in the response. Some representative plots are shown in Figs. 3.8 to 3 13. Here the operating conditions are assumed to be time invariant

3.7 Unavailability of Some of the States

Since all the states are not available, Observers are designed for reconstructing the unavailable states. The plant parameter matrices are to be known beforehand to design the Observers. But, these matrices are not known since they change with changing load conditions. We can use an adaptive Observer along with the state feedback adaptive controller. However, what happens when the two systems namely adaptive observer and adaptive controller designed separately are used together is not known. Another thing is

P=1, Q=0, Xe=0.35

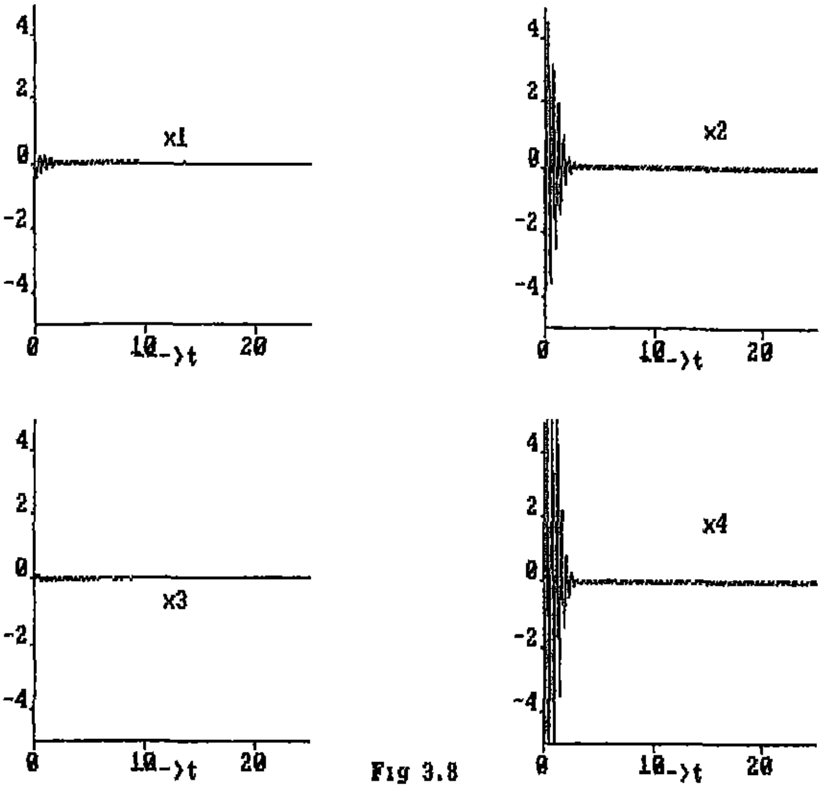


Fig 3.8

P=0.8, Q=0.6, Xe=0.35

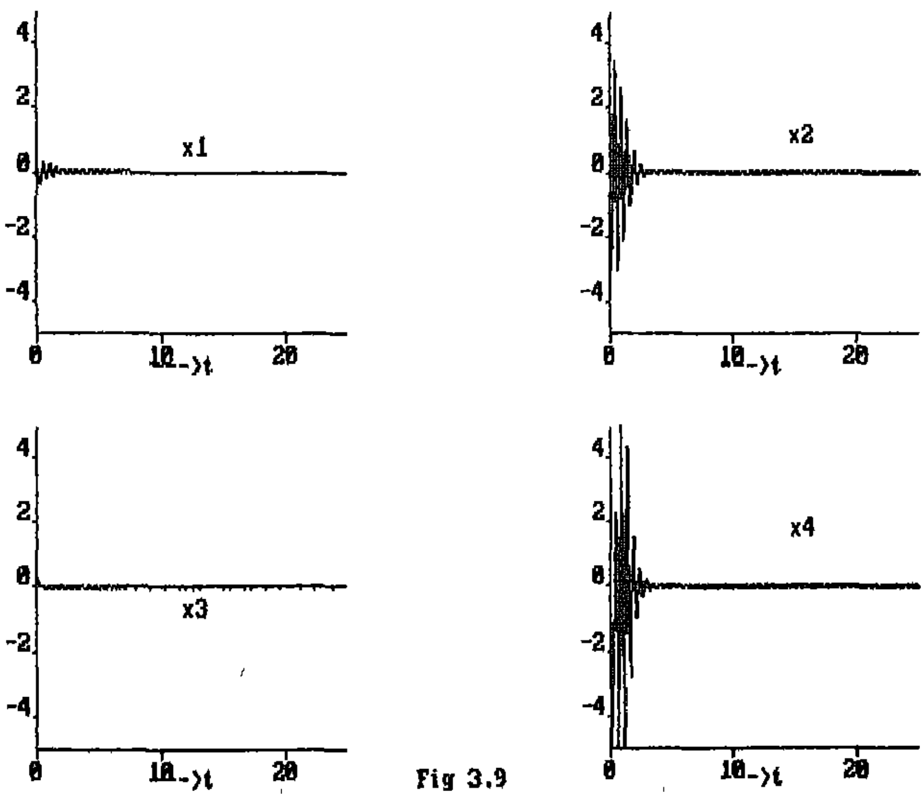


Fig 3.9

P=0.65, p.f =0.65, Xe=0.7

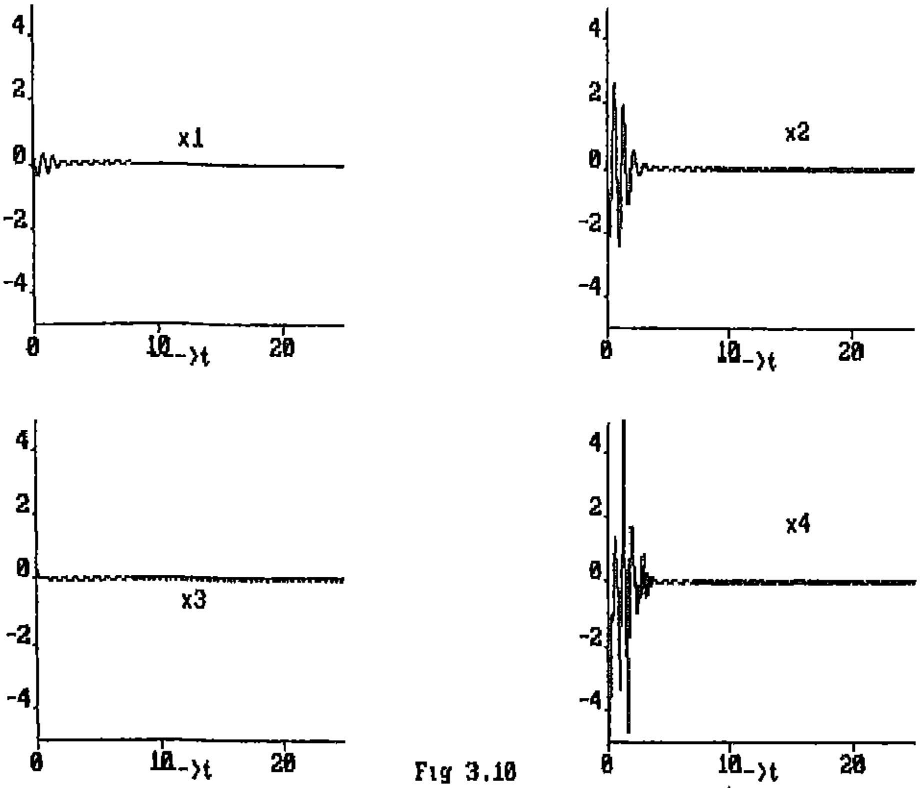


Fig 3.10

P=0.4 , p.f =0.4, Xe=0.7

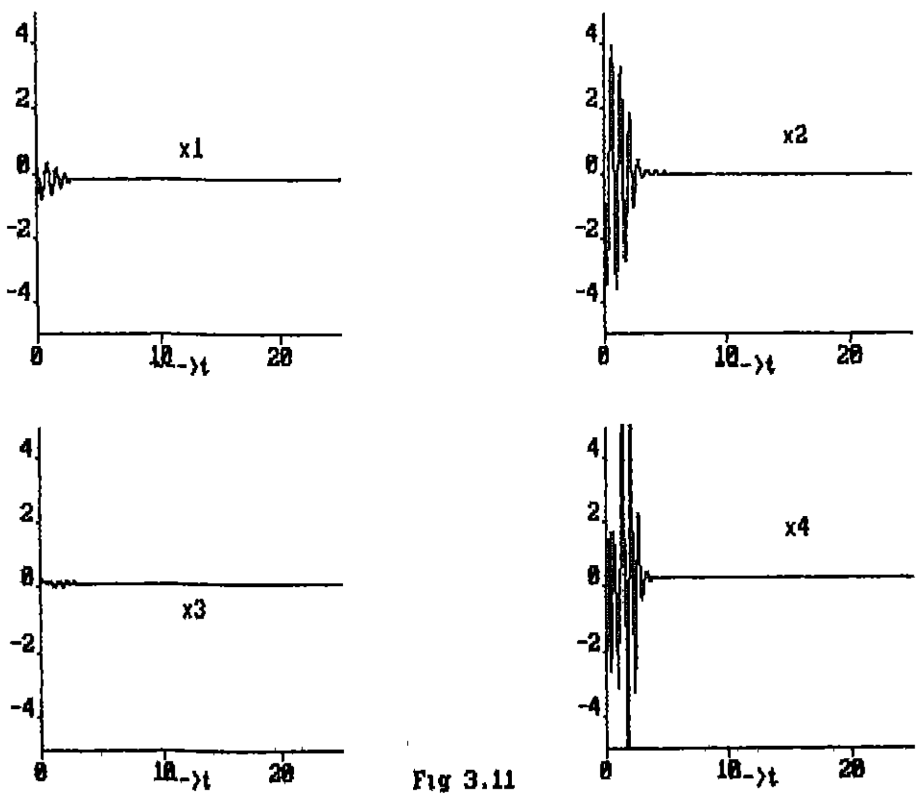


Fig 3.11

P=0.6, Q=-0.53, Xe=0.7

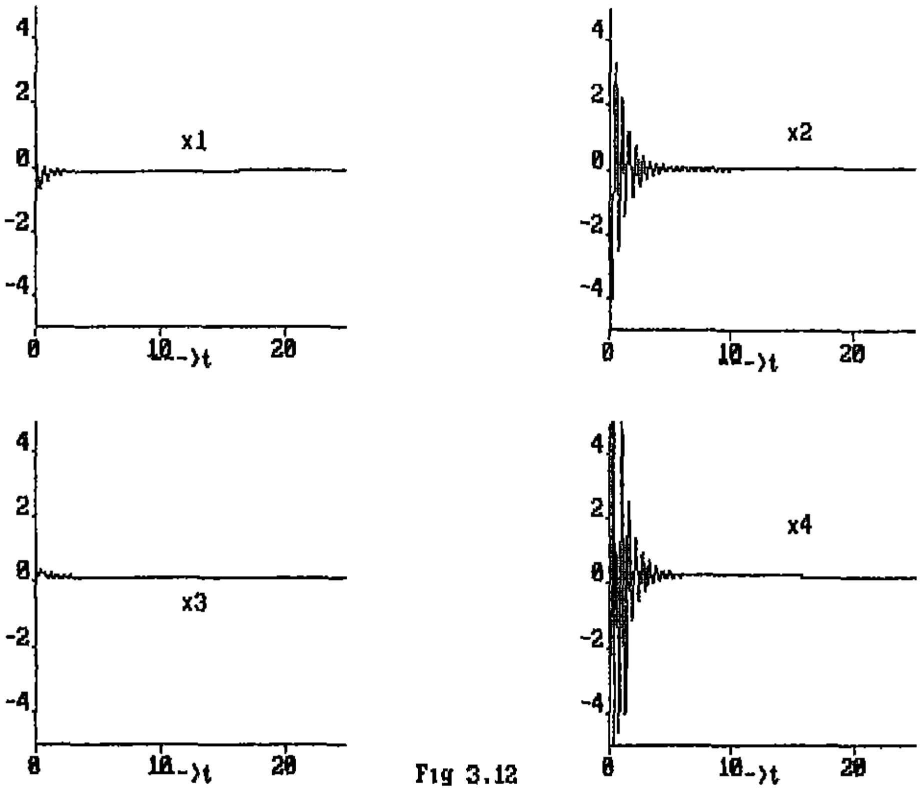


Fig 3.12

P=0.6, Q=0, Xe=1.4

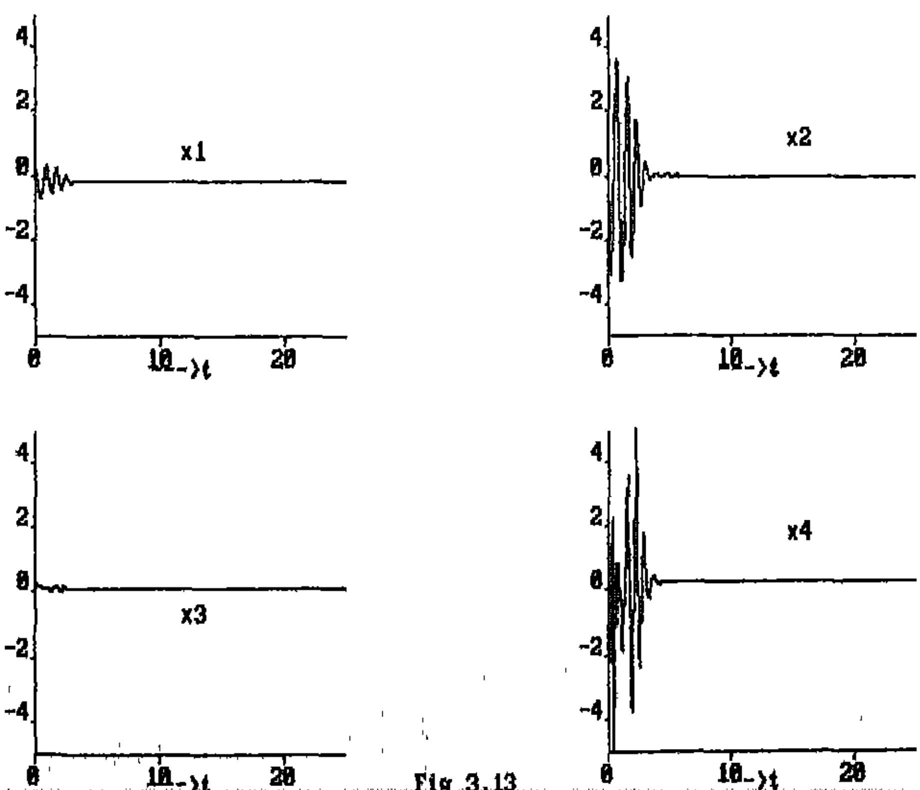


Fig 3.13

that the resulting system may be very complex limiting its use in practice. So, instead of the above approach, we have used the parameter matrices of the reference model for state observation and have studied how the system behaves with such an observer incorporated. Since, in steady, state the plant with the feedback controller is expected to converge to the reference model, it is hoped that, asymptotically the state observation leads to the actual state values of the plant. This observer design is straight forward , see for example [42].

3.8 Numerical Problem

3.8.1 Using First Order Observer

Assuming that δ_Δ , ω_Δ , $e_{fd\Delta}$ are available and $e'_{q\Delta}$ is not practically available (which is a reasonable assumption from the practical view point), a first order observer is constructed using the procedure given in Appendix 3. The final equations of the whole system consisting of the plant, the reference model, the adaptive controller and the observer are given below.

Plant:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= a_1x_1 + a_2x_3 \\ \dot{x}_3 &= a_3x_3 + a_4x_4 \\ \dot{x}_4 &= a_5x_1 + a_6x_3 + a_7x_4 + bu \end{aligned} \tag{3.33}$$

Reference Model:

$$\begin{aligned} \dot{x}_{m_1} &= x_{m_2} \\ \dot{x}_{m_2} &= a_{m_1}x_{m_1} + a_{m_2}x_{m_3} \\ \dot{x}_{m_3} &= a_{m_3}x_{m_3} + a_{m_4}x_{m_4} \\ \dot{x}_{m_4} &= a_{m_5}x_{m_1} + a_{m_6}x_{m_2} + a_{m_7}x_{m_3} + a_{m_8}x_{m_4} + br \end{aligned} \tag{3.34}$$

Controller:

$$u = k_1 x_1 + k_2 x_2 + k_3 \hat{x}_3 + k_4 x_4 \tag{3.38}$$

$$\dot{k}_1 = T_m \gamma_1 x_1$$

$$\dot{k}_2 = T_m \gamma_2 x_2$$

$$\dot{k}_3 = T_m \gamma_3 \hat{x}_3$$

$$\dot{k}_4 = T_m \gamma_4 x_4 \tag{3.39}$$

$$T_m = -b\,[\,p_1(x_1 - x_{m_1}) + p_2(x_2 - x_{m_2}) + p_3(\hat{x}_3 - x_{m_3}) + p_4(x_4 - x_{m_4})\,] \tag{3.40}$$

Observer:

$$\dot{z} = t_4 z + b_{m_3} u + t_1 x_1 + t_2 x_2 + t_3 x_4 \tag{3.41}$$

$$\hat{x}_3 = z - (m_1 x_1 + m_2 x_2 + m_3 x_4) \tag{3.42}$$

$$t_1 = m_2 a_{m_1} + m_3 a_{m_5} - m_1 t_4$$

$$t_2 = m_1 + m_3 a_{m_6} - m_2 t_4$$

$$t_3 = a_{m_4} + m_3 a_{m_8} - m_3 t_4$$

$$t_4 = a_{m_3} + m_2 a_{m_2} + m_3 a_{m_7} \tag{3.43}$$

$$M = [\,m_1\ m_2\ m_3\,] = [\,0\ 0\ 0.0095\,] \tag{3.44}$$

M is selected to place the eigen value of A_{11} at -20 (Appendix 3).

The system was simulated and it was found that it takes long time to settle down for all operating conditions. The plots of x(t) are shown for two operating conditions in Figs. 3.14 and 3.15.

3.8.2 Using Second Order Observer

We assume that δ_Δ and ω_Δ are available, $e'_{q\Delta}$ and $e_{fd\Delta}$ are not available. A second order observer is constructed for this situation using the procedure given in Appendix 4. The equations of the plant and reference model remain unchanged as in the previous case.

P=0.8, Q=0, Xe=0.7

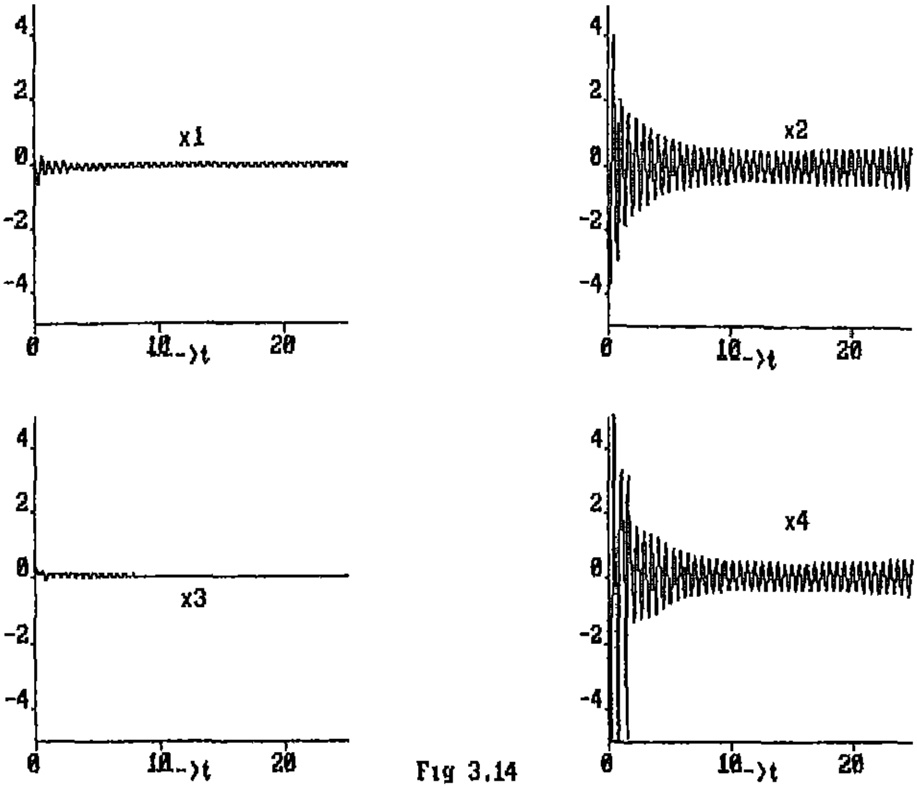


Fig 3.14

P=0.2, Q=-0.3464, Xe=1.4

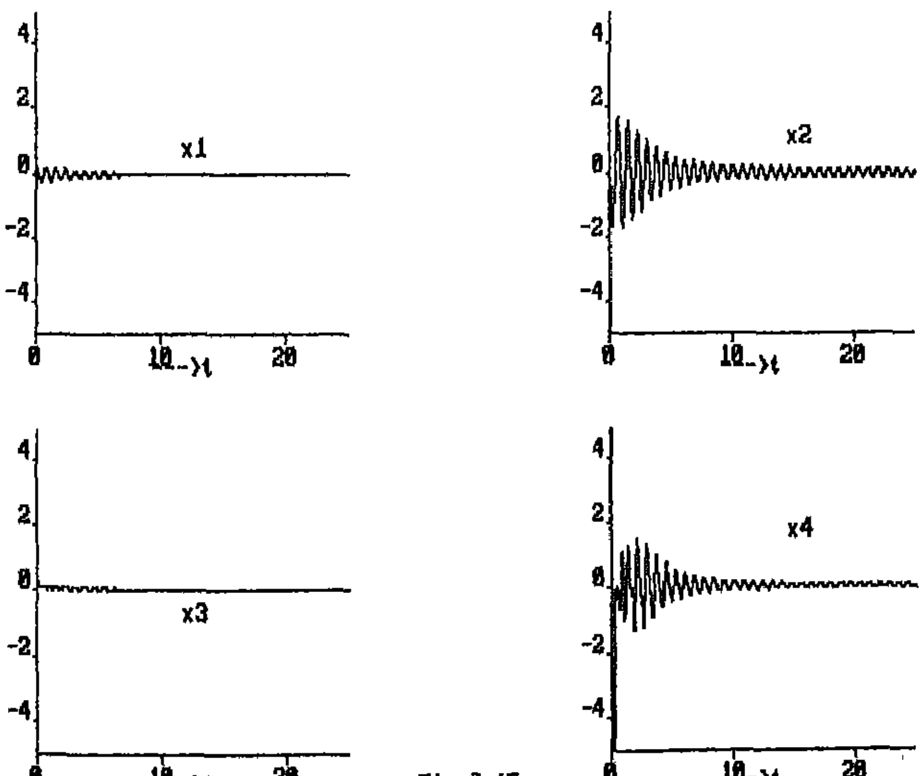


Fig 3.15

The equations of the controller and the observer are given below.

Controller:

$$u = k_1x_1 + k_2x_2 + k_3\hat{x}_3 + k_4\hat{x}_4 \tag{3.45}$$

$$\dot{k}_1 = T_m\gamma_1x_1$$

$$\dot{k}_2 = T_m\gamma_2x_2$$

$$\dot{k}_3 = T_m\gamma_3\hat{x}_3$$

$$\dot{k}_4 = T_m\gamma_4\hat{x}_4 \tag{3.46}$$

$$T_m = -b\,[\,p_1(x_1 - x_{m_1}) + p_2(x_2 - x_{m_2}) + p_3(x_3 - x_{m_3}) + p_4(x_4 - x_{m_4})\,] \tag{3.47}$$

Observer:

$$\dot{z}_1 = t_{52}z_1 + a_{m_4}z_2 + t_{12}x_1 + t_{22}x_2$$

$$\dot{z}_2 = t_{62}z_1 + a_{m_8}z_2 + t_{32}x_1 + t_{42}x_2 + bu \tag{3.48}$$

$$\hat{x}_3 = z_1 - m_1x_1 - m_2x_2$$

$$\hat{x}_4 = z_2 - m_3x_1 - m_4x_2 \tag{3.49}$$

t_{12}, t_{22}, t_{32}, t_{42}, t_{52} and t_{62} are defined in Appendix 4. We place the eigen values of A_{11} (Appendix 4) at –20, –93.3772.

Then

$$M = \begin{bmatrix} m_1 & m_2 \\ m_3 & m_4 \end{bmatrix} = \begin{bmatrix} 0 & 0.1178 \\ 0 & -2.6174 \end{bmatrix} \tag{3.50}$$

The system is simulated under different operating conditions and found that it does not give satisfactory performance for all the operating conditions considered. The plots of x(t) are shown in Figs. 3.16 and 3.17.

P=0.6, Q=0.53, Xe=1.4

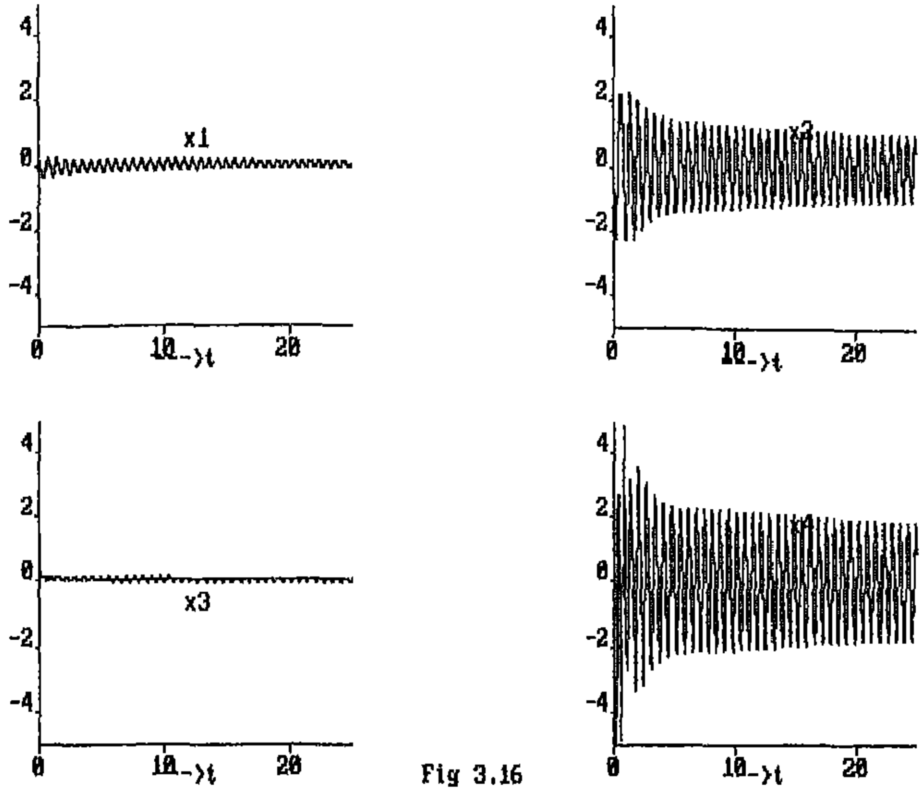
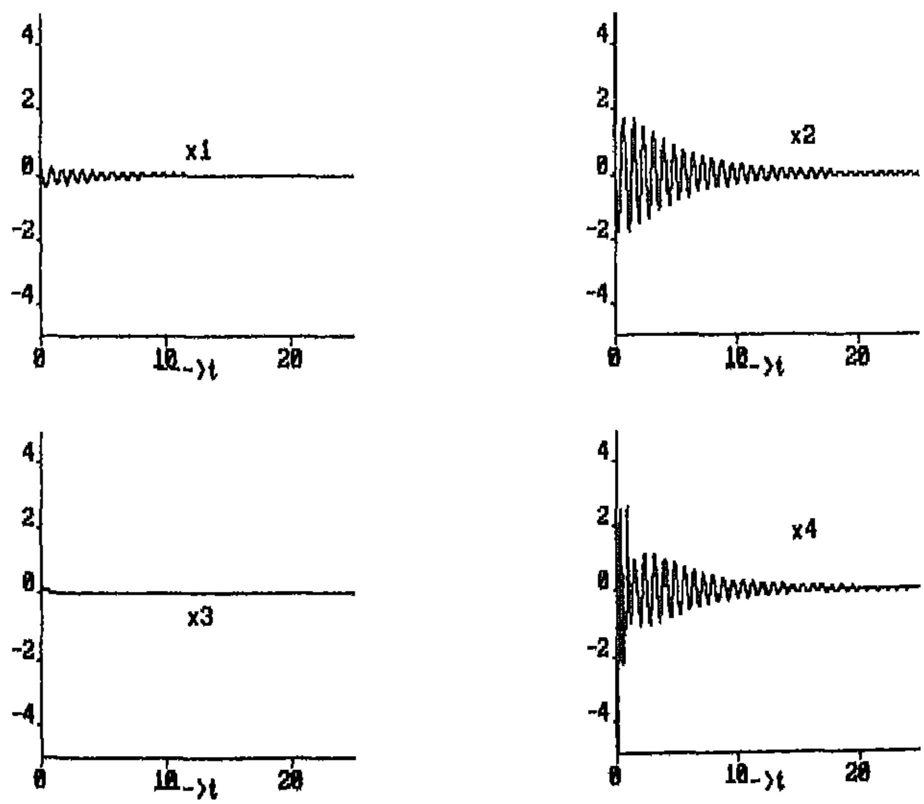


Fig 3.16

P=0.4, Q=0.0, Xe=1.4



3.8.3 Using Third Order Observer

We assume that only ω_Δ is available and δ_Δ , $e'_{q\Delta}$ and $e_{fd\Delta}$ are unavailable. For this case, third order observer is constructed using the procedure given in Appendix 5. The equations of the plant and reference model remain unchanged as in the previous cases. The equations of the controller and observer are given below.

Controller:

$$u = k_1\hat{x}_1 + k_2x_2 + k_3\hat{x}_3 + k_4\hat{x}_4 + r \tag{3.51}$$

$$\begin{aligned} \dot{k}_1 &= T_m\gamma_1\hat{x}_1 \\ \dot{k}_2 &= T_m\gamma_2x_2 \\ \dot{k}_3 &= T_m\gamma_3\hat{x}_3 \\ \dot{k}_4 &= T_m\gamma_4\hat{x}_4 \end{aligned} \tag{3.52}$$

$$T_m = -b\,[\,p_1(\hat{x}_1 - x_{m_1}) + p_2(x_2 - x_{m_2}) + p_3(\hat{x}_3 - x_{m_3}) + p_4(\hat{x}_4 - x_{m_4})\,] \tag{3.53}$$

Observer:

$$\begin{aligned} \dot{z}_1 &= m_1a_{m_1}z_1 + m_1a_{m_2}z_2 + t_{13}x_2 \\ \dot{z}_2 &= m_2a_{m_1}z_1 + (a_{m_3} + m_2a_{m_2})z_2 + a_{m_4}z_3 + t_{23}x_2 \\ \dot{z}_3 &= (a_{m_5} + m_3a_{m_1})z_1 + (a_{m_7} + m_3a_{m_2})z_2 + a_{m_8}z_3 + t_{33}x_2 + bu \end{aligned} \tag{3.54}$$

$$\begin{aligned} \hat{x}_1 &= z_1 - m_1x_2 \\ \hat{x}_3 &= z_2 - m_2x_2 \\ \hat{x}_4 &= z_3 - m_3x_2 \end{aligned} \tag{3.55}$$

t_{13} , t_{23} and t_{33} are defined in Appendix 5.

The system was simulated and it was found that the controller along with this third order observer gives very satisfactory performance over a large range of operating conditions and the system settles down quickly following a disturbance. The plots are shown in Figs. 3.18 to 3 23.

So, from the above study we can say that the presented model reference adaptive PSS works very satisfactorily, when only ω_{Δ} is available, the other states being reconstructed using a third order observer. It should be mentioned here, that traditionally only the speed signal ω_{Δ} is used as input to the conventional nonadaptive PSS.

Rated load ,0.9 pf, Xe=0.7

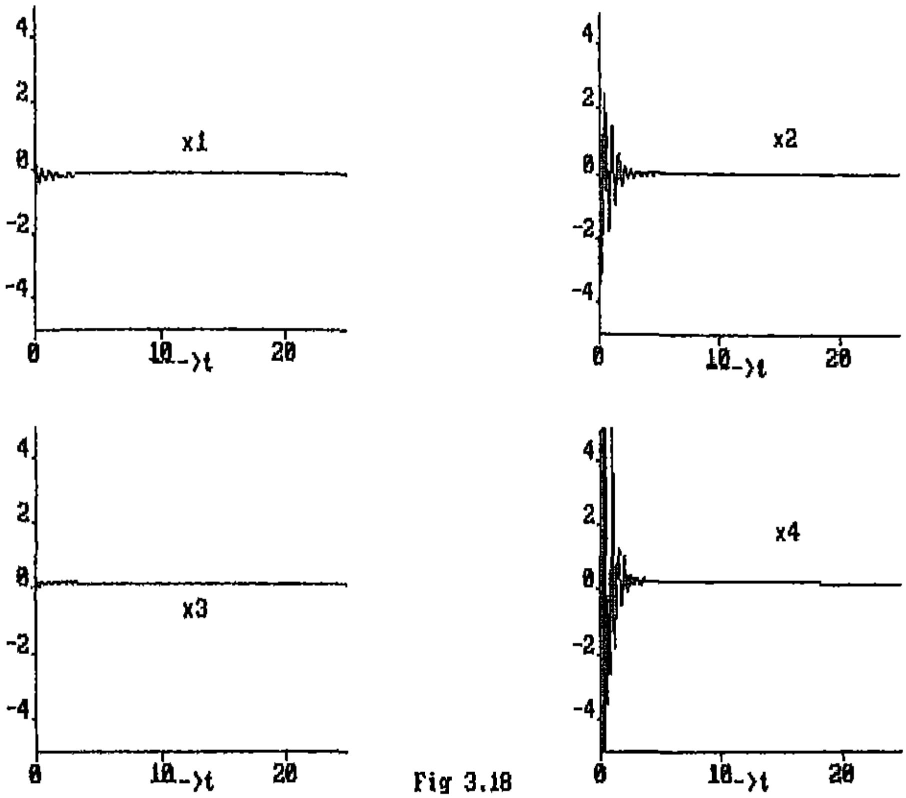


Fig 3.18

P=0.6, Q=0.0, Xe=1.4

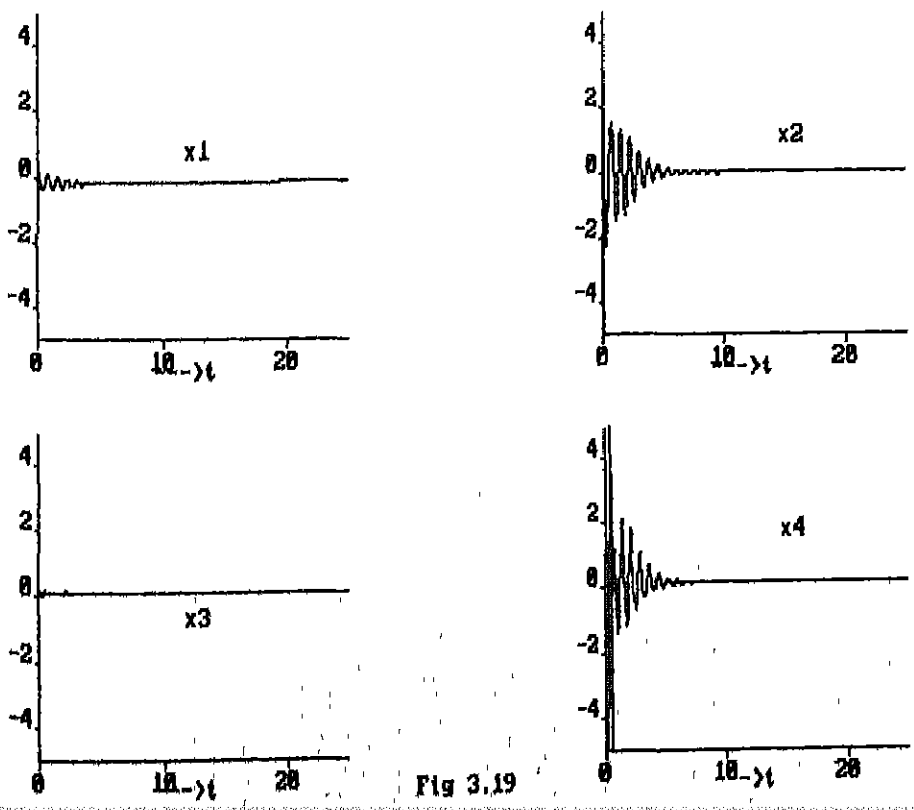


Fig 3.19

P=0.8, Q=0.0, Xe=0.7

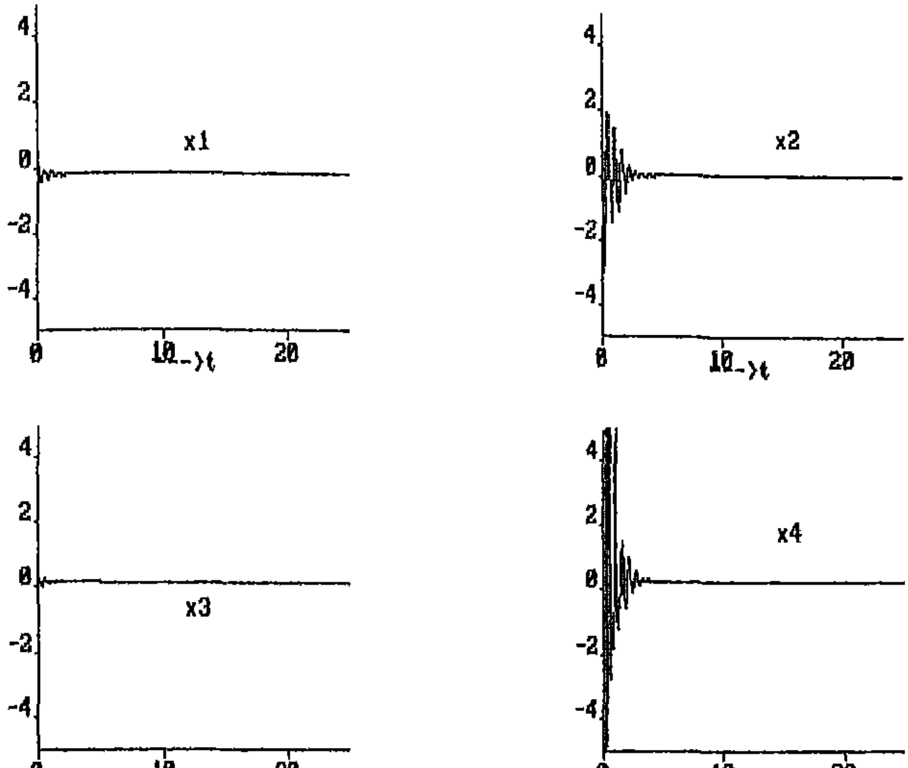


Fig 3.20

Rated load, 0.4 pf, Xe 0.7

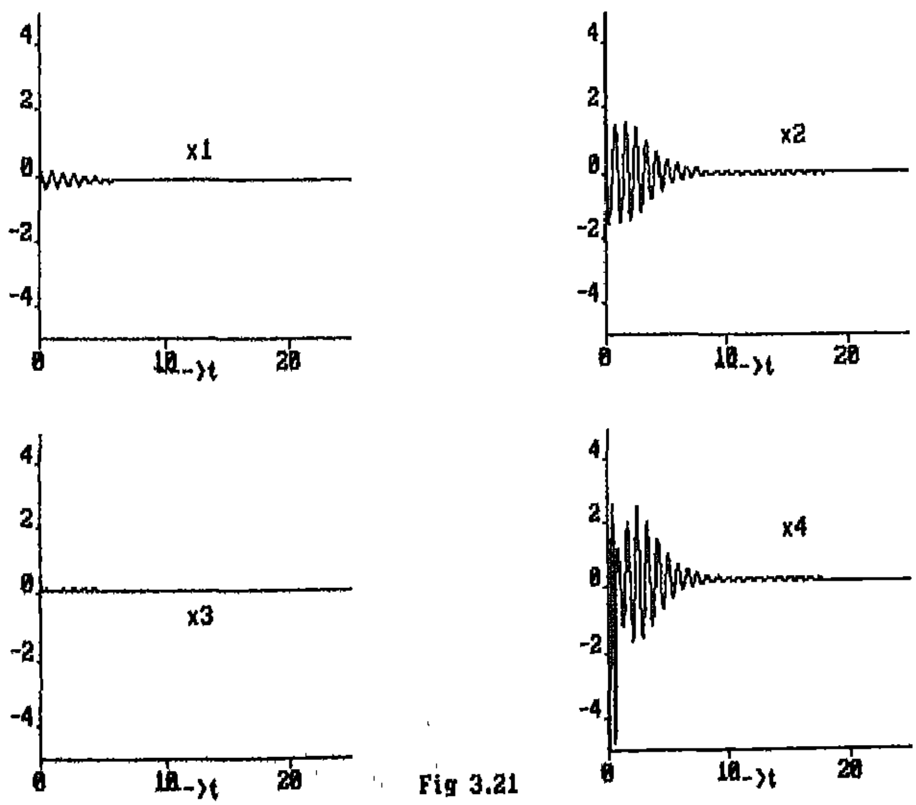


Fig 3.21

P=0.4, Q=-0.6928 Xe=1.4

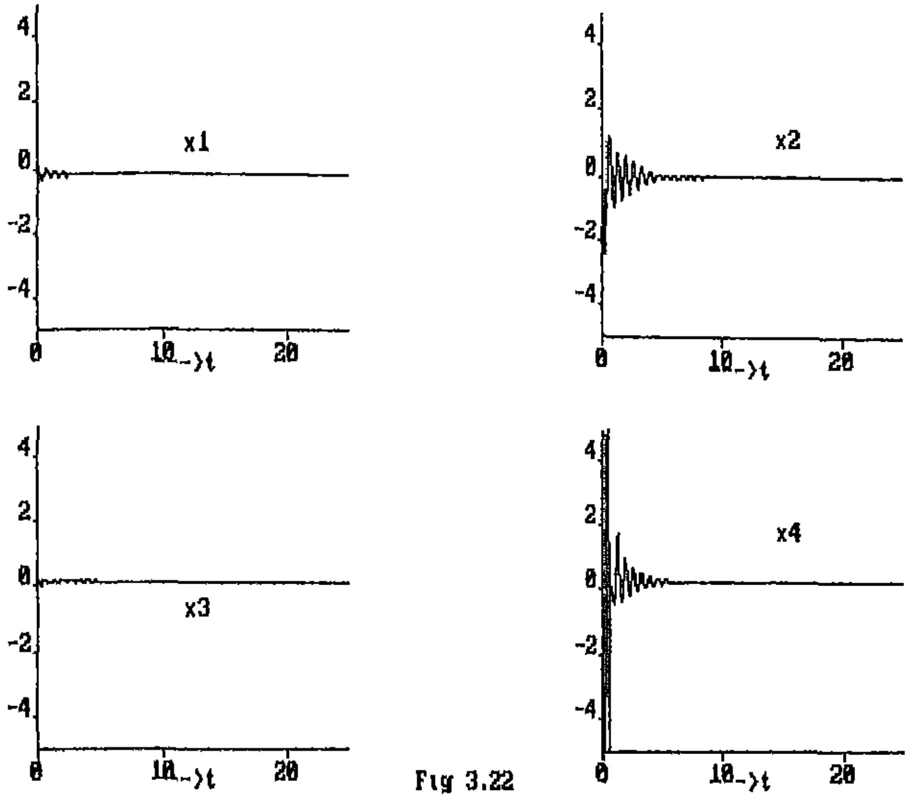


Fig 3.22

P=0.2, Q=-0.7746, Xe=1.4

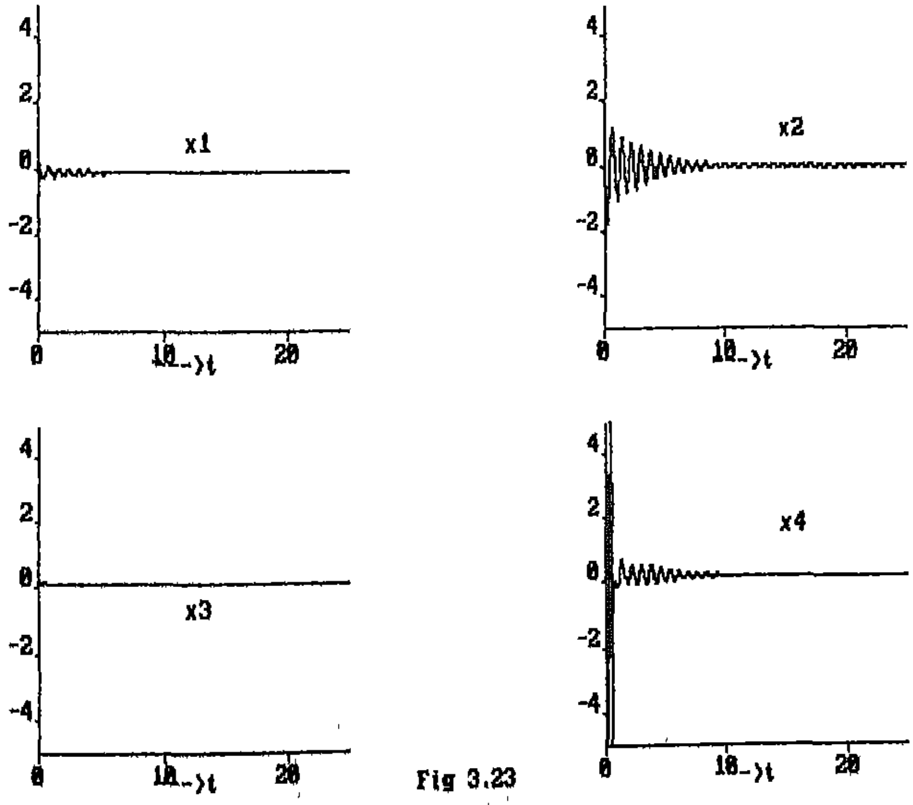


Fig 3.23

CHAPTER 4
CONCLUSIONS

4.1 Conclusions

Fast acting, high gain modern voltage regulators often cause low frequency sustained oscillations in power systems. The conventional non adaptive PSS, used to damp out these oscillations, can not perform satisfactorily over a wide range of operating conditions. Modern control techniques involve use of model reference adaptive control or gain scheduling for the design of PSS to overcome this problem. MRAC is easier than STR and good adaptation speeds can be achieved. Further, this technique ensures the stability of the system which is lacking in STR techniques. In the present work, we have used MRAC technique for the design of PSS to a power system consisting of an alternator connected to an infinite bus through a transmission line. By simulating the overall system under various operating conditions, it has been shown that the PSS works satisfactorily over a wide range of operating conditions. This design of PSS requires the feedback of all the state variables. Since, in practice, all the state variables are not available, the unavailable states are reconstructed using observers and the performance of the system is studied by simulating over a wide range of operating conditions. The observers used the parameters of the reference model.

It has been shown that an observer which reconstructs $e'_{q\Delta}$, $e_{fd\Delta}$ and δ_Δ using knowledge of only ω_Δ, gives highly satisfactory results, over a wide range of operating conditions, when used in conjunction with the state feedback MRAC scheme. It should be noted that for conventional PSS ω_Δ is the commonly used input signal. Thus with the conventionally available instrumentation with generators, the proposed adaptation scheme can easily be implemented. This is a significant finding of this thesis.

4.2 Scope for Further Work

There is scope for extending the present work to the following areas.

1. In practice, a power system consists of very large number of machines. So, the present study can be extended to multi machine systems.

2. MRAC schemes using hyperstability approach can be developed to investigate if simpler and better controllers can be achieved.

3. Here, we have used a linearised model of synchronous machine. This work can be extended to the design of MRAPSS using an exact nonlinear model of alternator and the results can be validated by simulation on a micromachine system

4. It can be investigated whether a MRAC scheme in conjunction with a conventional PSS will yield simpler and better adaptive controllers

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APPENDIX 1
MODEL OF POWER SYSTEM (Heffron–Philips Model)

The power system considered consists of a synchronous generator connected to an infinite bus through a transmission line as shown in Fig. A.1.1. The well–known Heffron Philips model for such a power system which represents the linear small signal system dynamics around an operating point can be given using standard notation, as below (see for example [34]):

$$e'_{q\Delta} = \frac{K_3}{1 + K_3 \tau'_{d0} s} e_{fd\Delta} - \frac{K_3 K_4}{1 + K_3 \tau'_{d0} s} \delta_\Delta$$

$$P_{e\Delta} = K_1 \delta_\Delta + K_2 e_{q'\Delta}$$

$$V_{t\Delta} = K_5 \delta_\Delta + K_6 e'_{q\Delta}$$

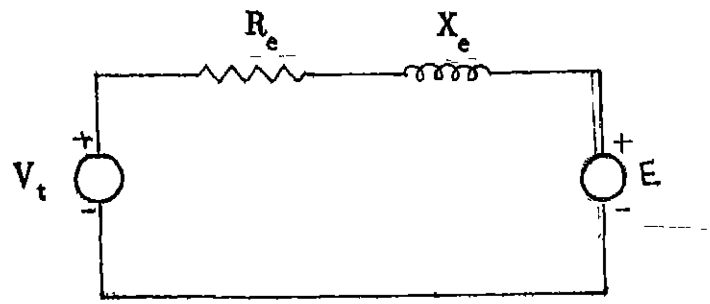

Fig A.1.1 Generator Connected to An Infinite Bus

Through a Transmission line

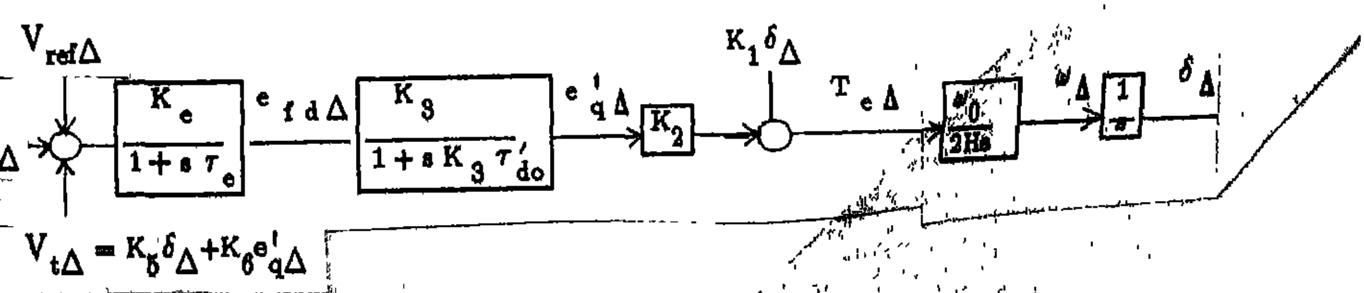

Fig A.1.2 Block Diagram of Power System

Swing equations:

$$\frac{2H}{\omega_0}\dot{\delta}_\Delta = P_{m\Delta} - P_{e\Delta} \qquad (A.1\,1)$$

where all quantities are in p.u except δ_Δ and ω_Δ which are expressed in radians and radians/sec, respectively. The coefficient K_4 is usually small and can be neglected. Furthermore, turbine–governor dynamics can be neglected which implies that $P_{m\Delta}$ can be set equal to zero. With these approximations, the power system can be represented in the block diagram form as in Fig. A 1.2.

The power system Heffron Philips model can be represented in state space form as

$$\begin{aligned}
\dot{\delta}_\Delta &= \omega_\Delta \\
\dot{\omega}_\Delta &= \left(\frac{-K_1\omega_0}{2H}\right)\delta_\Delta + \left(\frac{-K_2\omega_0}{2H}\right)e'_{q\Delta} \\
\dot{e}'_{q\Delta} &= \left(\frac{-1}{K_3\tau'_{do}}\right)e'_{q\Delta} + \left(\frac{1}{\tau'_{do}}\right)e_{fd\Delta} \\
\dot{e}_{fd\Delta} &= \left(\frac{-1}{\tau_e}\right)e_{fd\Delta} + \left(\frac{-K_eK_5}{\tau_e}\right)\delta_\Delta + \left(\frac{-K_eK_6}{\tau_e}\right)e'_{q\Delta} + \left(\frac{K_e}{\tau_e}\right)u
\end{aligned} \qquad (A1.2)$$

Defining

$$\begin{aligned}
a_1 &= \left(\frac{-K_1\omega_0}{2H}\right) & a_2 &= \left(\frac{-K_2\omega_0}{2H}\right) \\
a_3 &= \left(\frac{-1}{K_3\tau'_{do}}\right) & a_4 &= \left(\frac{1}{\tau'_{do}}\right) \\
a_5 &= \left(\frac{-1}{\tau_e}\right) & a_6 &= \left(\frac{-K_eK_5}{\tau_e}\right) \\
a_7 &= \left(\frac{-K_eK_6}{\tau_e}\right) & b &= \left(\frac{K_e}{\tau_e}\right)
\end{aligned} \qquad (A.1.3)$$

Then, the power system can be represented by the equation

$$\dot{x} = Ax + Bu$$

where $x = [\,\delta_\Delta \;\; \omega_\Delta \;\; e'_{q\Delta} \;\; e_{fd\Delta}\,]^t$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ a_1 & 0 & a_2 & 0 \\ 0 & 0 & a_3 & a_4 \\ a_5 & 0 & a_6 & a_7 \end{bmatrix}$$

and $B = [\,0 \;\; 0 \;\; 0 \;\; b\,]^t$

APPENDIX 2
SYNCHRONOUS MACHINE AND POWER SYSTEM DATA

The power system data considered is given below (values are in PU to machine base whereever relevant).

Generator Parameters:

$X_d = 1.14$, $X_q = 0.66$ $X_d' = 0.24$,

$\tau_{do}' = 5.0$ sec, $K_e = 50$ $\tau_e = 0.01$ sec,

$H = 1.5$ sec, $\omega_0 = 314.0$ rad/sec.

Network Parameters:

$R_e = 0\ 024$, $X_e = 0\ 7$ and $V_T = 1.0$ PU,

where

X_d , X_d' are the direct axis synchronous and transient reactances respectively,

X_q is the quadrature axis synchronous reactance,

τ_{do}' is the direct axis transient open circuit time constant,

K_e and τ_e are the gain and time constants of the exciter respectively,

H is the inertia constant of the synchronous machine,

ω_0 is the nominal synchronous speed,

R_e and X_e are the resistance and inductive reactance of the transmission line.

APPENDIX 3
CONSTRUCTION OF FIRST ORDER OBSERVER

We assume that δ_Δ , ω_Δ , $e_{fd\Delta}$ are available and $e'_{q\Delta}$ is not available. Since the parameter matrices A and B of the plant are not known, the observer is designed using the parameter matrices A_m and B_m of the model.

So

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ a_{m_1} & 0 & a_{m_2} & 0 \\ 0 & 0 & a_{m_3} & a_{m_4} \\ a_{m_5} & a_{m_6} & a_{m_7} & a_{m_8} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ b \end{bmatrix} u$$

and

$$y = [\, x_1 \, x_2 \, x_4 \,]^t \tag{A.3.1}$$

Since the output vector consists of x_1 , x_2 and x_4 , the state equations can be expressed in standard form, [42], as

$$\begin{bmatrix} \dot{x}_3 \\ \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} a_{m_3} & 0 & 0 & a_{m_4} \\ 0 & 0 & 1 & 0 \\ a_{m_2} & a_{m_1} & 0 & 0 \\ a_{m_7} & a_{m_5} & a_{m_6} & a_{m_8} \end{bmatrix} \begin{bmatrix} x_3 \\ x_1 \\ x_2 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ b \end{bmatrix} u \tag{A.3 2}$$

From [42] the observer is given by

$$\dot{z} = (A_{11} + MA_{21})z + (B_1+MB_2)u + [A_{12}+MA_{22} - (A_{11}+MA_{21})M]y \tag{A.3.3}$$

$$\hat{x} = \begin{bmatrix} I \\ 0 \end{bmatrix} z + \begin{bmatrix} -M \\ I \end{bmatrix} y \tag{A.3.4}$$

where $M = [m_1\ m_2\ m_3\ ]$ is chosen to place the eigen values of $A_{11}+MA_{21}$ at any desired locations

Here

$$A_{11} = [a_{m_3}]$$

$$A_{12} = [0\ \ 0\ \ a_{m_4}],$$

$$A_{21} = [0\ \ a_{m_2}\ \ a_{m_7}]^t$$

$$A_{22} = \begin{bmatrix} 0 & 1 & 0 \\ a_{m_1} & 0 & 0 \\ a_{m_5} & a_{m_6} & a_{m_8} \end{bmatrix}$$

$B_1 = [0]$ and

$$B_2 = [0\ 0\ b]^t \qquad \text{(A.3.5)}$$

We can derive the following equations for the observer by substituting equation (A.3.5) in equations (A.3.3) and (A.3 4)

$$\dot{z} = t_4 z + b_{m_3} u + t_1 x_1 + t_2 x_2 + t_3 x_4, \qquad \text{(A.3.6)}$$

$$\hat{x}_3 = z - (m_1 x_1 + m_2 x_2 + m_3 x_4), \qquad \text{(A.3.7)}$$

$$t_1 = m_2 a_{m_1} + m_3 a_{m_5} - m_1 t_4,$$

$$t_2 = m_1 + m_3 a_{m_6} - m_2 t_4,$$

$$t_3 = a_{m_4} + m_3 a_{m_8} - m_3 t_4,$$

$$t_4 = a_{m_3} + m_2 a_{m_2} + m_3 a_{m_7}. \qquad \text{(A.3.8)}$$

The equations (A.3.6), (A.3.7) and (A.3.8) describe the required first order observer. Note that $\hat{x}_3$ is the value of the state variable $e'_{q\Delta}$ of the plant as given by the observer and x_1, x_2 and x_4 are the state variables δ_Δ, $e'_{q\Delta}$ and $e_{fd\Delta}$ respectively of the plant

APPENDIX 4
CONSTRUCTION OF SECOND ORDER OBSERVER

We assume that δ_Δ and ω_Δ are available and $e_{fd\Delta}$ and $e'_{q\Delta}$ are not available. Since the parameter matrices A and B of the plant are not known, the observer is designed using the parameter matrices A_m and B_m of the model.

So

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ a_{m_1} & 0 & a_{m_2} & 0 \\ 0 & 0 & a_{m_3} & a_{m_4} \\ a_{m_5} & a_{m_6} & a_{m_7} & a_{m_8} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ b \end{bmatrix} u$$

and

$$y = [\, x_1 \; x_2 \,]^t \tag{A.4.1}$$

Since the output vector consists of x_1 and x_2, the state equations can be expressed in standard form, [42], as

$$\begin{bmatrix} \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} a_{m_3} & a_{m_4} & 0 & 0 \\ a_{m_7} & a_{m_8} & a_{m_5} & a_{m_6} \\ 0 & 0 & 0 & 1 \\ a_{m_2} & 0 & a_{m_1} & 0 \end{bmatrix} \begin{bmatrix} x_3 \\ x_4 \\ x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ b \\ 0 \\ 0 \end{bmatrix} u \tag{A.4.2}$$

From [42] the observer is given by

$$\dot{z} = (A_{11} + MA_{21})z + (B_1 + MB_2)u + [A_{12} + MA_{22} - (A_{11} + MA_{21})M]y \tag{A.4.3}$$

$$\hat{x} = \begin{bmatrix} I \\ 0 \end{bmatrix} z + \begin{bmatrix} -M \\ I \end{bmatrix} y \tag{A.4.4}$$

where

M is a 2x2 matrix chosen to place the poles of $A_{11} + MA_{21}$ at any desired locations.

$$M = \begin{bmatrix} m_1 & m_2 \\ m_3 & m_4 \end{bmatrix}$$

Here

$$A_{11} = \begin{bmatrix} a_{m_3} & a_{m_4} \\ a_{m_7} & a_{m_8} \end{bmatrix}$$

$$A_{12} = \begin{bmatrix} 0 & 0 \\ a_{m_5} & a_{m_6} \end{bmatrix}$$

$$A_{21} = \begin{bmatrix} 0 & 0 \\ a_{m_2} & 0 \end{bmatrix}$$

$$A_{22} = \begin{bmatrix} 0 & 1 \\ a_{m_1} & 0 \end{bmatrix}$$

$B_1 = [0 \ \ b]^t$ and

$B_2 = [0 \ \ 0]^t$ (A.4.5)

We can derive the following equations for the observer by substituting equatio (A.4.5) in equations (A.4.3) and (A.4.4)

$$\dot{z}_1 = t_{52}z_1 + a_{m_4}z_2 + t_{12}x_1 + t_{22}x_2$$

$$\dot{z}_2 = t_{62}z_1 + a_{m_8}z_2 + t_{32}x_1 + t_{42}x_2 + bu \qquad (A\,4{\cdot}6)$$

$$\hat{x}_3 = z_1 - m_1x_1 - m_2x_2$$

$$\hat{x}_4 = z_2 - m_3 x_1 - m_4 x_2 \tag{A.4.7}$$

Where

$$t_{12} = m_2 a_{m_1} - m_1 t_{52} - m_3 a_{m_4},$$

$$t_{22} = m_1 - m_2 t_{52} - m_4\, a_{m_4},$$

$$t_{32} = a_{m_5} + m_4 a_{m_1} - m_1 t_{62} - m_3 a_{m_8},$$

$$t_{42} = a_{m_6} + m_3 - m_2 t_{62} - m_4 a_{m_8},$$

$$t_{52} = a_{m_3} + m_2 a_{m_2} \quad \text{and}$$

$$t_{62} = a_{m_7} + m_4 a_{m_2} \tag{A.4.8}$$

The equations (A.4.6), (A.4.7) and (A.4.8) describe the required second order observer. Here $\hat{x}_3$ and $\hat{x}_2$ are the state variables $e'_{q\Delta}$ and $e_{fd\Delta}$ as reconstructed by the observer. The variables x_1 and x_2 are the state variables δ_Δ and ω_Δ respectively of the plant.

APPENDIX 5
CONSTRUCTION OF THIRD ORDER OBSERVER

We assume that only ω_Δ is available and $e_{fd\Delta}$, δ_Δ and $e'_{q\Delta}$ are not available. Since the parameter matrices A and B of the plant are not known, the observer is designed using the parameter matrices A_m and B_m of the model.

So

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ a_{m_1} & 0 & a_{m_2} & 0 \\ 0 & 0 & a_{m_3} & a_{m_4} \\ a_{m_5} & a_{m_6} & a_{m_7} & a_{m_8} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ b \end{bmatrix} u$$

and

$$y = [\, x_2 \,] \tag{A.5.1}$$

Since the output vector consists of only x_2, the state equations can be expressed in standard form, [42], as

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & a_{m_3} & a_{m_4} & 0 \\ a_{m_5} & a_{m_7} & a_{m_8} & a_{m_6} \\ a_{m_1} & a_{m_2} & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_3 \\ x_4 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ b \\ 0 \end{bmatrix} u \tag{A.5.2}$$

From [42] the observer is given by

$$\dot{z} = (A_{11} + MA_{21})z + (B_1+MB_2)u + [A_{12}+MA_{22} - (A_{11}+MA_{21})M]y \tag{A.5.3}$$

$$\hat{x} = \begin{bmatrix} I \\ 0 \end{bmatrix} z + \begin{bmatrix} -M \\ I \end{bmatrix} y \tag{A.5 4}$$

where

M is a 3x1 matrix chosen to place the poles of $A_{11} + MA_{21}$ at any desired locations.

$$M = [\, m_1 \;\; m_2 \;\; m_3 \,]^t$$

Here,

$$A_{11} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & a_{m_3} & a_{m_4} \\ a_{m_5} & a_{m_7} & a_{m_8} \end{bmatrix}$$

$$A_{12} = [\, 1 \;\; 0 \;\; a_{m_6} \,]^t$$

$$A_{21} = [\, a_{m_1} \;\; a_{m_2} \;\; 0 \,]$$

$$A_{22} = [\, 0 \,] \qquad B_1 = [\, 0 \;\; 0 \;\; b \,]^t \text{ and}$$

$$B_2 = [\, 0 \,] \tag{A 5.5}$$

We can derive the following equations for the observer by substituting the equation (A.5.5) in the equations (A.5.3) and (A.5.4):

$$\dot{z}_1 = m_1 a_{m_1} z_1 + m_2 a_{m_2} z_2 + t_{13} x_2$$

$$\dot{z}_2 = m_2 a_{m_1} z_1 + (a_{m_3} + m_2 a_{m_2}) z_2 + a_{m_4} z_3 + t_{23} x_2$$

$$\dot{z}_3 = (a_{m_5} + m_3 a_{m_1}) z_1 + (a_{m_7} + m_3 a_{m_2}) z_2 + a_{m_8} z_3 + t_{33} x_2 + bu \tag{A.5.6}$$

$$\hat{x}_1 = z_1 - m_1 x_2$$

$$\hat{x}_3 = z_2 - m_2 x_2$$

$$\hat{x}_4 = z_3 - m_3 x_2 \tag{A.5.7}$$

where

$$t_{13} = 1 - m_1^2\, a_{m_1} - m_1 m_2 a_{m_1}$$

$$t_{23} = -\,[m_1 m_2 a_{m_1} + m_2(a_{m_3} + m_2 a_{m_2}) + m_3 a_{m_4}]$$

$$t_{33} = a_{m_6} - [m_1(a_{m_5} + m_3 a_{m_1}) + m_2(a_{m_7} + m_3 a_{m_2}) + m_3 a_{m_8}]$$

(A.5.8)

The equations (A.5.6), (A.5.7) and (A.5.8) describe the required third order observer. Here $\hat{x}_1$, $\hat{x}_3$ and $\hat{x}_4$ are the variables δ_Δ , $e'_{q\Delta}$ and $e_{fd\Delta}$ as reconstructed by the observer. The variable x_2 is the state variable ω_Δ of the plant.